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Sediment transport & alluvial resistance in rivers

R&D Technical Report W5i 609

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Environment Agency

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Steve Killeen

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Head of Science

Executive summary

This manual describes issues related to sediment transport and alluvial resistance in rivers. The implications of sediment transport and alluvial resistance for both channel design and maintenance are discussed. Many river engineering schemes have a morphological impact. It is important that these should be understood, predicted and were possible avoided. A knowledge of sediment transport and alluvial resistance can help in the specification of maintenance work so that unnecessary maintenance work is avoided.

The manual describes concepts used in discussing sediment issues in rivers. Any study of sediment transport requires data and so methods for the acquisition and analysis of sediment related data are described.

There is a chapter devoted to determining the flow conditions at which sediment begins to move, initiation of motion. This addresses the problem of both uniform and non-uniform sediments and also effects that occur at small depth/diameter ratios.

Different sediment transport theories are described which predict bed load and total bed material load. Examples of the use of different theories are given. Most sediment transport theories are derived from laboratory data. The problems that arise in applying these theories to natural river channels are discussed.

Different theories for predicting alluvial resistance are described and examples given of their use.

Sediment aspects of river morphology and fluvial processes are described. The manual deals with natural channel shape, slope and plan form. Processes related to bank erosion are described. Reservoir sedimentation and sediment deposition on floodplains is described.

Sediment on the bed of a river forms the substrate for many of the habitats associated with rivers. The nature and movement of sediment on the bed of a channel can thus have a major impact on the riverine environment. There is a section devoted to environmental issues which describes how sediment issues can affect the environment.

Finally there is a brief section on methods for studying the wide range of sediment problems that may arise within a river system.

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1.1 Introduction to Sediment in Rivers

Rivers not only convey water but they also transport sediment from the catchment to the sea or outfall of the river. Under most circumstances the flow of water forms both the river channel and the plan form of the river. As a result, all natural rivers are subject to change, either through erosion, deposition or plan form change. River engineering works are normally carried out to alter the flow of water in some way. Such changes normally also result in altering the sediment movement within the channel and hence the channel shape and plan form.

Sediment processes, by shaping the river channel, also affect the flow conditions in a river and hence the conveyance of a river, the distribution of velocity and depth and the composition of the bed sediments. Thus sediment processes are intimately connected with both flood defence and also the ecology of rivers.

Thus sediment processes are of interest to:
- those concerned with the design or appraisal of flood defence schemes,
- those concerned with river maintenance and,
- those interested in conservation and fisheries.

Some of the present sediment problems that engineers face arise from engineering works carried in the past when less consideration was given to such problems. It is hoped that this manual will raise the awareness of river engineers to some of the problems that can occur. In this way it is hoped that many potential problems can be avoided at the design stage, or, if they are unavoidable, can be quantified and minimised. It is also important to ensure that maintenance is carried out in such a way as to minimise sediment related problems.

In the past sediment aspects of rivers have been approached from different directions. Engineers have concentrated on the development of quantitative methods to predict changes within the sediment system over a relatively short period of time, normally less than 100 years. A branch of geography has now been developed called fluvial geomorphology, which is dedicated to the study of rivers and river shape. Initially geomorphology was more concerned with broad river development over geological timescales and the main concern was descriptive. It has gradually been realised in fluvial geomorphology that the details of the processes involved are important and also the necessity to work in quantitative terms rather than just qualitatively. Meanwhile engineers have realised that many sediment related problems can only be understood within the context of the general geomorphology of the river. The result is that there is an increasing overlap in the nature of the work carried out by both groups. This development is to be welcomed and it is hoped that a mutual exchange of ideas will lead to further advances in the field.

The authors of this manual have been brought up in the engineering tradition and, as a result, there is a concentration on the use of quantitative methods to predict changes within the river system. The overall geomorphology of the system should not, however, be forgotten as this may provide an understanding of the processes involved and may also suggest, for any particular problem, which types of solution may be most practicable.

1.2 Relevance to Design of Flood Defence Works

For the flood defence engineer, changes in bed level, channel size or shape, alluvial resistance or plan form will influence water levels and may lead to:
- increased risk of flooding,
- increased maintenance,
- failure of structures or
- bank failure.

Alluvial resistance is of importance to flood defence engineers as changes in alluvial resistance will affect water levels and hence may affect flood defence schemes. If the overall hydraulic roughness changes due to changes in alluvial resistance then flood defence schemes may fail to meet design conditions. If the alluvial resistance during a major flood is less than the design value then water levels will not achieve their design value and the scheme will be over-designed. If the alluvial resistance is higher than the design value then there is a danger that the scheme will be under-designed. Changes in the magnitude of alluvial resistance with flow may also create problems when calibrating fixed hydraulic roughness parameters in numerical models to observed data. Alterations to the hydraulic roughness during a flood event may mean that it is not possible to match the observed and calculated water levels for both the low and high discharges during a single flood event. They may also result in changes to the hydraulic roughness from one flood event to another.

1.3 Relevance to River Maintenance

Sediment movement, in particular sediment erosion or deposition, may present problems for those concerned with river maintenance. Sediment deposition due, for example, to an over widened channel can result in a long term maintenance commitment and cause environmental disturbance.

The aim should be to minimise the disturbance to the channel. This may only be possible if proper account of sediment was made during the design of a scheme. If maintenance work is carried out the issues that arise often include:
- how much sediment should be removed?
- will there be an impact upstream or downstream?
- will sediment changes continue in the future?

The development of bed features may present problems for those concerned with river maintenance. If bed features develop a number of maintenance issues often arise including:
- if a bed feature is removed what impact will that have on water levels, ecology and fisheries?
- will there be an impact upstream or downstream?
- will the bed feature reform and if so,
- how quickly will the feature reform?

1.4 Relevance to Conservation and Fisheries

The bed sediments in a river provide the substrate for the fluvial eco-systems. The composition of the bed sediments is thus an important factor in many river habitats. This bed sediment composition is entirely determined by the sediment processes within the river system. An important factor in the development of eco-systems is also the frequency of movement of the sediments.

Bed features should not just be considered from the point of view of their impact on channel conveyance. The development of bed features may provide a wider range of habitats than might otherwise be present. One of the more obvious types of bed features that are commonly found in gravel rivers is pool-riffle sequences. These systems provide a wide range of habitats, add to the visual appearance of a river and are important in a number of aspects of fisheries. Riffles can be important for the spawning of fish while pools can be important as holding areas and for food. Major bed features, such as bars, affect the depth and velocity of flow which have an impact on the attractiveness of a reach of river to fish and on the river's appearance.

1.5 Introduction to Manual

This manual provides information on sediment processes in rivers and their significance. While the manual contains much standard information that is available elsewhere in the literature, recent research findings have also been included where possible.

Chapter 2 reviews the sediment issues related to design and maintenance. Chapter 3 introduces concepts and definitions associated with sediment and sediment movement that are used throughout the rest of the Manual. Any sediment study relies upon data collected in the field. Chapter 4 considers the collection and analysis of sediment data. The determination of the conditions when sediment is just on the point of moving, initiation of motion is described in Chapter 5. Chapter 6 describes theories involved with sediment movement, including initiation of motion, bed load and total load. These theories have normally been based on the assumption of a well-defined flow velocity and depth. In natural rivers there are significant spatial variations in both flow and sediment properties. The problems that these variations introduce are discussed in Chapter 7. Chapter 8 is devoted to the subject of alluvial resistance and its prediction. More general issues of river morphology and fluvial processes are described in Chapter 9. Sediment is an important aspect of the physical habitat provided by rivers and so has important links with the riverine environment and Chapter 10 is devoted to these environmental issues. Chapter 11 is a brief introduction to the range of analytical methods that are available for the study of sediment problems in rivers.

There is also a recently published guidebook that is very relevant to the contents of this manual (Sear et al , 2003). It is strongly recommended that this guidebook is read in conjunction with the present manual.

2 Design and Maintenance

2.1 Introduction

Rivers carry sediment from a catchment to the outfall of the river, usually the sea. The movement of the sediment depends upon the flows in the river and has been likened to a jerky conveyor belt. In considering river works the impact on sediment and sediment movement should be taken into account.

The size and plan form of rivers are not random but depend upon the nature of the flow, sediment and topography. Though our understanding of the physics is far from perfect, there is a belief that, under particular conditions, there is a stable, but not static river form. If a river reach does not conform to these stable conditions then it is likely that morphological change will take place, which may lead to expensive maintenance or remedial work.

The input of water and sediment to a river system may vary though time. The consequence is that changes will take place to the river system. Thus river systems are often described as being in ‘dynamic equilibrium’. While the physical processes may have resulted in stable systems the continual change in the input conditions may lead to continuous change within the system. While many such changes to the input parameters are random in nature, for example, wet years and dry years, there is a growing appreciation that there may be systematic changes in the driving forces, for example, climate change or land use change. Such changes have the potential to cause long-term changes to the river system.

In considering either design or maintenance, careful consideration should be given to sediment issues as failure to address them properly can lead to significant future problems and, in some cases, to substantial costs (HR, 1987 and Fisher, 1992). Table 2.1, taken from Fisher (1992), identifies a range of morphological problems that can arise from river improvement works. Any engineering works should take account of the natural sediment processes. Failure to do this can lead to unanticipated expensive maintenance, failure to achieve design objectives, or both. As described in this manual, methods are available to allow the quantitative prediction of the impact of schemes on sediment processes. These methods should be applied as part of the design process or to investigate the impact of proposed maintenance regimes in order to assess the likely consequences of proposed works. For convenience, in this chapter design and maintenance are considered separately although some of the issues are similar.

2.2 Design of River Works

2.2.1 Introduction

As described above, for any given conditions, there is a stable river form to which a river system will tend to regress naturally. To minimise sediment problems, the designer should strive, therefore, to ensure that the design is as close as possible to a stable river form for the given conditions.

It may be, however, that within the given constraints it is not possible to achieve a stable form. A possibly extreme example of this is the construction of a reservoir. It is in the nature of reservoirs that sedimentation will take place in the reservoir. All a designer can do in this case is to predict the likely morphological change in the future and, if possible, to minimise it, perhaps by the use of sediment flushing. Where a stable form is not achievable, the designer still has a responsibility to determine the likely future maintenance commitment and, where possible, to minimise it.

Table 2.1 Details and morphological problems of selected river improvement works

Scheme	**River**	*Scheme Details*	**Subsequent problems**	**Maintenance**
East Mill improvement scheme	River Colne	New sluice gates, channel enlargements, flood embankments	Silt accumulation	Silt removal
River Stour improvement scheme, Bures to Cornard	River Stour	Channel deepening, flood embankments, new weirs	Erosion at weir, weed growth	Grass cutting
Duffield improvement scheme	River Ecclesbourne	Concrete channel, channel widening, re-alignment, bank protection, flood walls	Sediment accumulation. Erosion of revetment	Sediment removal
Brecon improvement scheme	River Usk	Channel regrading, flood embankments, bridge alterations, widening and deepening of channel upstream of Llanfaes bridge	Silt accumulation upstream of Llanfaes bridge	5,000 to 8,000 tonnes of gravel removed on two occasions since 1979
Aylesford Stream improvement scheme	Aylesford stream	Channel widening and deepening, bridges removed or reconstructed, re-alignment of channels, concrete flume section, flood embankments	Weed growth, deposition of silt and sand	Yearly weed clearance, dredging of sand and silt
River Sence improvement scheme	River Sence	Channel widening, deepening and re-alignment	Deposition of sand and silt. Vegetation growth, bank erosion	Dredging and vegetation clearing

2.2.2 Issues for design of river works

The designer of river works should consider the following issues:

a) *sediment transport rate*. Rarely do river works alter the whole length of a river. If only a reach of river is affected then the sediment transport rate upstream and downstream will remain unaffected. If the design does not ensure that the sediment transport rate in the modified reach matches that upstream and downstream then either erosion or deposition is likely to occur. See Chapter 6.

b) *alluvial resistance.* The design should take account of the hydraulic roughness that is likely to develop in the design reach. See Chapter 8.

c) *channel size and shape.* For a given discharge, sediment load and sediment size there is a stable channel size and shape, often referred to as the regime channel. If another size or shape is adopted then it is likely that erosion or deposition will take place to make the channel correspond more closely to regime conditions. See Chapter 9.

d) *plan form*. The design should take account of the natural plan form of the river. Attempts to straighten a river are often difficult and, in the long-term, fruitless unless a large amount of effort is expended on river training or maintenance. See Chapter 9.

e) *bank stability*. River works may lead to bank failure. This may introduce extra sediment into the fluvial system and result in further problems either upstream or downstream. See Chapter 9.

Good design should take into account the stable river morphology and should also consider and quantify the need for subsequent maintenance.

2.2.3 Morphological impact of typical river engineering works

River improvement schemes are carried out for a number of purposes including flood defence and river restoration. In such schemes the work is normally confined to a reach of the river. If the sediment conditions and particularly the sediment transport rate in the modified reach does not match that in the reaches upstream and downstream then erosion or deposition will occur. The impact may not necessarily be confined to the modified reach but may extend both upstream and downstream. The matching of sediment transport rates in the modified reach with those in the reach upstream and downstream will not necessarily be sufficient to avoid sediment related problems, for example:

a) modifications to water levels can lead to bank failure,

b) within the modified reach selection of an inappropriate channel shape may lead to erosion and possible bank failure or may lead to deposition,

c) the selection of an inappropriate plan form shape may lead to bank erosion and plan form change. Such bank erosion may increase the sediment load in the river channel and hence lead to sedimentation further downstream.

The precise impact of engineering works is very site specific and depends upon the nature of the river and the details of the work that is carried out. From experience at a range of sites (see HR 1992) it is possible, however, to give an indication of the likely impact of different types of engineering works, see below. The occurrence and severity of such problems should be predicted and quantified as part of the design process. Again, the appropriate methods of study are site specific and depend upon the amount of data available but Table 2.2 gives an indication of the type of methods that can be used to assess a range of problems.

The morphological impact of a range of typical river engineering works is now described:

a) *channel straightening*. This reduces the length of the river channel but maintains the same loss of height. It also removes the head loss due to the bends. As a result the water surface slope in the straightened reach is increased, the velocity is increased and the depth of flow reduced. The increased water surface slope and velocity leads to increased sediment transport rates in the straightened reach. If the upstream sediment load is unaltered this in turn leads to erosion in the straightened reach as well as further upstream, and sediment deposition downstream of it.

b) *construction of flood embankments*. Depending upon their position on the floodplain, flood embankments may alter the velocity and depth of flow in the main channel and hence the overall sediment transporting capacity of the reach. This can commonly reduce the sediment transporting capacity of the main channel and hence lead to sediment deposition. The resulting increase in bed levels may, in the long term, reduce the effectiveness of the flood embankments. If the embankments encroach significantly, the flow velocities adjacent to the embankment may increase to values at which bank erosion may take place unless the embankments are properly protected.

c) *flood relief channels*. By reducing the discharge in the main channel, flood relief channels will reduce the sediment transporting capacity of the original river channel. In general the combined cross-sectional area of the original river channel and the flood relief channel will exceed that of the original river channel during floods. As a result, average flow velocities are reduced and hence the sediment transport rate is also reduced. Sedimentation can frequently result in a reduction of the conveyance capacity of the channel to below the design value.

d) *reservoirs.* On-line storage reservoirs modify the flow distribution downstream but they also trap sediment. The common impact on flow distribution is for the flood peaks downstream to be reduced. This modifies the capacity of the channel to transport sediment. The frequent response is for the channel to reduce in size. The impact of the reduced sediment load from upstream as a result of the sediment being trapped in the reservoir is for the bed of the river downstream to degrade and the bed sediments to coarsen. Changed flows, channel size and bed substrate may have a significant impact on the flora and fauna in the reach downstream.

Table 2.2 Potential sediment impact of a range of typical river engineering works

Type of works	Potential sediment impact	Other impacts	Method of study
Dams and weirs (downstream impacts)	Degradation, bank failure Armouring of bed, reduced suspended sediment load	Changed habitats Temperature effects Release of pollutants from bank material	Numerical model
Dams and weirs (upstream impacts)	Sedimentation Reduced sediment size on bed	Changed habitats Weed growth	Numerical model
Channel widening or deepening	Sediment deposition Changed sediment size on bed Bank failure	Loss of channel conveyance Changed habitats Release of pollutants	Desk method or numerical model
Embankments	Sediment deposition Changed sediment size on bed	Loss of channel conveyance Changed habitats Increased flows downstream	Desk methods or numerical model
Channel re-alignment	Sediment deposition Sediment erosion Bank erosion	Changed habitats Release of pollutants	Desk methods or numerical model
Construction of weirs/sluices	Sediment deposition upstream Sediment erosion, bank erosion and bank failure downstream	Weed growth upstream Release of pollutants	Desk methods or numerical model
Reduced flows	Sediment deposition	Weed growth Loss of channel conveyance Changed habitats	Desk methods or numerical model
Increased flows	Sediment erosion Bank erosion Bank failure	Changed habitats Release of pollutants	Desk methods or numerical model

The cost of not considering sediment problems during the design phase may result in unnecessarily large maintenance costs or, in extreme cases, failure of the scheme.

2.2.4 Sustainability of schemes from the morphological point of view

If a reach of river is to be modified then to avoid morphological problems one needs to satisfy the following conditions:

- the long-term average sediment transport rate should remain the same as that for the original reach,
- the channel size and shape should conform to regime conditions
- the plan form should be appropriate for the particular channel.

For river diversion schemes it is sometimes possible to satisfy all these conditions. The objective of flood defence schemes is normally to increase the conveyance in a reach and this objective is often incompatible with the strict fulfilment of all of the above conditions. In such circumstances a compromise is required. It should be remembered that such a compromise is likely to lead to some form of sediment related problem but it is the responsibility of the designer to predict and minimise such problems. It is also the responsibility of the designer to predict and accurately cost the level of maintenance that will be required for such a scheme.

To ensure that the long-term average sediment transport rates correspond with those in the reaches upstream and downstream it is necessary to carry out a number of calculations. These should be done for a range of discharges from initiation of motion increasing up to large, rare events. If the sediment is widely graded then the calculations should be for an appropriate range of sediment sizes and should include hiding effects. Most natural rivers show a large natural variability between sections, even ones that are closely spaced. In general, it will not be sufficient to perform the calculations at only one section in each reach. It is recommended, therefore, that the calculations are performed at a number of sections. If this is the case then it may prove easier to use a one-dimensional numerical model to perform the calculations. In interpreting the results it must be remembered that the predictions of sediment transport equations are not precise. Small differences in sediment transport rate between sections will probably be accommodated by small changes in channel form and slope. If large differences in sediment transport rate are predicted and these are unavoidable then the differences in sediment transport should be used to calculate the resulting annual amount of erosion or deposition. This can be used to assess the likely maintenance commitments.

Where a channel is being designed to take a particular discharge, the dimensions of the channel should either be checked against those in the undisturbed reaches upstream and downstream or against predictions based on regime theory. To use regime theory it will be necessary to select a dominant discharge. This may be done on the basis of:

a) the determination of the discharge that transports the most sediment. This is likely to involve a long and complicated set of calculations
b) the bank full discharge
c) the discharge with a fixed return period. In the absence of any further information it is suggested that a 2 to 3 year return period is used.

The channel size should then be selected to correspond to the regime predictions. Failure to do this may cause erosion or deposition leading to significant changes in the shape of the river channel.

2.2.5 The implications of variable alluvial resistance

If the scheme involves the selection or modification of the plan form of a river then the appropriate plan form of the channel should be considered. Failure to do this may lead to major morphological changes in the river system. Lewin (1976) describes the impact of plan form change on the River Ystwyth in mid-Wales. A meandering reach of the river had first been straightened in 1864 as part of the construction of a railway. Since then the river had reverted to a meandering course. In 1969 the river was straightened once more. After a single winter with only a total of 75 hours of flows capable of moving sediments significant changes had already taken place. A pattern of alternating gravel bars and bank erosion had developed. The thalweg sinuosity had increased to 1.2 and bank erosion equivalent to 50% of the original channel area had taken place in some areas. This demonstrates that the process of plan form change may take place rapidly in rivers with unprotected banks. This example is in no way unusual. Most corners of the world are littered with examples of unsuccessful attempts to interfere with the plan form of rivers. Long-term change can normally only be brought about by carrying out major and expensive engineering works to permanently stabilise the river banks.

It should be assumed that the plan form of a river may change in the future. In many cases changes to the river plan form may take place during the lifetime of a project. A railway bridge was constructed on a meandering river approximately 100 years ago. When the bridge was constructed the piers were well-aligned with the flow. Since construction the meander pattern has progressed down the river valley with the result that the bridge piers are now poorly aligned with the flow and a scour problem has resulted. Channel plan form is discussed in Chapter 9.

The main implication of alluvial resistance is that the hydraulic roughness of a channel is not fixed but will vary with flow. For flood defence the main concern is the impact that this may have on flood flows. Let us assume that the capacity of a channel has been assessed on the basis of a value of hydraulic roughness determined during normal flows. If the hydraulic roughness reduces as the flow increases then the capacity of the channel will have been underestimated and the actual capacity of the channel will be greater than that calculated. If the hydraulic roughness increases with flow then the capacity of the channel will have been overestimated and flooding might then result.

An example of this was given by Hogg et al (1988). Measurements of water level and discharge were taken at Sukkur barrage during a flood in 1976. Initially, at a discharge of 8,500 cumecs, the Mannings n value was 0.014. As the discharge increased the n value fell to 0.012 before rising as the peak flow was reached. Around the time of the peak flow there was a sudden increase in the n value to approximately 0.024 followed by a more gradual increase to 0.029 as the flow receded, see Figure 2.1. Hogg et al attributed the increase in Mannings n value to changes in the nature of the bed forms. The increase in Mannings n value had a significant impact on water levels and bed levels and raised the issue as to what was the appropriate n value to assume for the design of flood embankments. In the transition from upper to lower regime flow the bed level changed by approximately 3 m while the water level changed by approximately 1 m.

The impact of changes in alluvial resistance during a flood may make the interpretation of observed water levels difficult. If a hydraulic roughness coefficient is calculated from observed water levels corresponding to one particular discharge then that hydraulic roughness coefficient may not be appropriate for other discharges, either larger or smaller. Possible changes in channel cross-section during a flood associated with erosion or deposition will only compound the problem. If water levels collected at a range of discharges indicate varying values of the hydraulic roughness, it may be difficult to determine to what extent they are due to variations in alluvial resistance and to what extent they are influenced by changes in the channel shape during the flood.

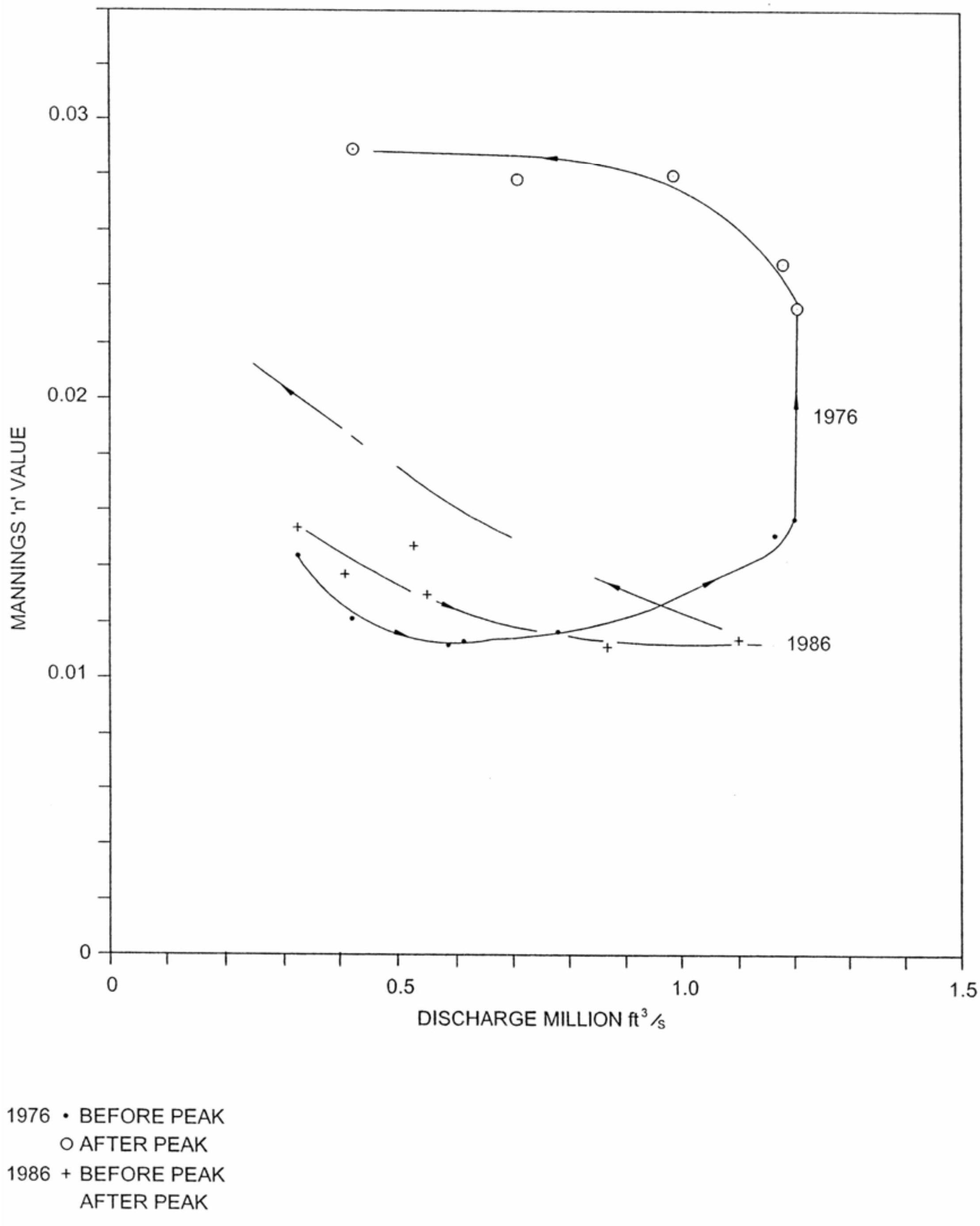


Figure 2.1 Manning's n value at Sukkur Barrage, Indus during the 1976 and 1986 floods

The variation of alluvial resistance during a flood event may also be a source of problems when calibrating numerical models that only incorporate fixed roughness coefficients. In this case, it may not be possible to obtain a good calibration for a wide range of flow conditions, and it may be that the model will only correctly reproduce the flow behaviour for a restricted range of flows.

It is thus of the greatest importance to design engineers to assess the roughness of a channel and whether it may change as the flow conditions change.

2.2.6 Impact of construction in or near rivers

It is also important to consider the impact of temporary works on the river system. Such works can rapidly generate large and sometimes adverse changes to a river system. For example constructing a coffer dam in a river may lead to:
- the erosion of adjacent banks,
- local scour around the coffer dam,
- changes to the size and shape of the deepest part of the channel,
- local deposition of sediment in the lee of the coffer dam.

Such changes may:
- adversely affect flood levels in the river,
- affect other structures in the neighbourhood,
- permanently affect the development of the river system.

It is quite common for construction sites near or in rivers to release large quantities of sediment into the adjacent river (Goldman et al 1986). This can have a severe impact on the river and particularly on the ecology of the river. River fauna may be particularly vulnerable to increased sediment concentrations. The problem is particularly acute in gravel bed rivers in which the bed of the river is armoured. If the surface armour layer is disturbed then the finer underlying sediment will be exposed to the flow and significant amounts of fine sediment can be released into the flow. In many cases the risk of the release of large quantities of sediment can be reduced by careful selection of the method of working. An important issue can also be the time of the year when the work is undertaken. Fish populations are normally at their most vulnerable during and shortly after spawning. Another consideration is the time of year when high flows are most likely. If this period can be avoided when carrying out the work then there is less chance of sediment being mobilised. Thus sediment issues should be very carefully considered when planning and carrying out construction in or near rivers.

2.3 River Maintenance

2.3.1 Introduction

Maintenance work is normally carried out periodically to maintain some characteristic of the river system. Examples of the characteristics that can be maintained include channel conveyance and navigation depth. The type of work that is carried out as maintenance varies with both the characteristic being maintained and the nature of the river. In general, it is beneficial if the amount of maintenance can be minimised, consistent with the constraints of the river system, as maintenance is both costly and disruptive to the environment. Periodic maintenance work suppresses natural environment development and hence reduces diversity and habitat value.

Just as good design should take account of the natural forms of rivers, maintenance should also be sensitive to river morphology as failure to take account of river morphology may lead to excessive and expensive maintenance work.

An existing maintenance requirement can frequently arise out of capital works carried out in a river in the past. Channel realignment, straightening and deepening have frequently been carried out in the past which has lead to erosion of the bed or banks in the altered reach and increased sediment load entering the downstream reach thereby causing further problems downstream. Experience has shown that a wide range of river works can cause maintenance requirements; these include:

- construction of embankments,
- flood relief channels and
- flood storage reservoirs.

Land-use change in the catchment upstream can also create maintenance requirements. If river schemes are to be sustainable then they should be designed for no or minimum maintenance.

The potential impact of a range of typical maintenance works are considered:

a) *dredging to maintain channel conveyance*. This reduces the water surface slope and velocity of flow in a reach and hence reduces the sediment transport rate. If the sediment inflow from upstream remains the same then sediment deposition will take place. The rate of sediment deposition will depend upon the upstream sediment concentrations and the change in the flow conditions induced by the works. Dredging may also increase the bank height, which can lead to bank failure.

b) *re-grading a channel*. Altering the slope of a channel will alter the sediment transport rate in the reach. An increase in slope will lead to an increase in the sediment transport rate and a reduction in slope will lead to a reduction in the sediment transport rate. If the sediment inflow from upstream remains the same then an increase in slope will lead to erosion and a reduction in slope will lead to deposition.

c) *shoal removal*. If bars or other bed features are removed then there may be no increase in channel conveyance and the bars may rapidly reform, see Chapter 8

d) *channel straightening*. The straightening of river channels or the removal of bars, unless accompanied by river training or bank protection works, are unlikely to provide a permanent change to the river system as the river is likely to rapidly re-adopt it original form.

River maintenance problems can arise from a number of causes, some of which may be connected with changes in the catchment upstream. Urbanisation of a catchment may lead to both increased urban run-off and peakier flood events. This may lead to increased sediment transport. This commonly results in erosion and increases in the size of channels. In an urban area such channel change may threaten parts of the urban development and in the past has often resulted in the construction of major river works that, in effect, channelise the river into a flume with inerodible bed and banks.

Depending upon the location of the urban areas within the catchment, enhanced sediment deposition may also occur downstream.

Urbanisation is a particular form of land-use change. Other types of land use changes may also affect either the flows or the sediment production of a catchment. The response to such changes may be both complex and develop over many years. One extreme example is forestation which often involves deep ploughing for drainage and to enable planting. This can result in a significant increase in the sediment production from the catchment. As the trees grow and the cover develops, the sediment production can drop to very low levels. The eventual logging of the mature trees can once again significantly increase the sediment production. These effects can be partly controlled by suitable management of the processes involved.

Sand or gravel abstraction from a river may also result in severe problems. Such sediment abstraction reduces bed levels both upstream and downstream from the location where the sediment is removed. The reduced bed levels lead to increased bank heights which can, in turn, induce bank failures. Changed water surface slopes can induce river plan form change. Bed level reductions may threaten structures upstream or downstream. The discharge of sediment into a river, for example the disposal of mine tailings, can also induce major changes in a river system. In this case the bed level will rise both upstream and downstream. The resulting change in water surface slope may also induce major plan form change.

In situations where bed features are known to develop and to impact on flood levels then there is an obvious temptation to remove these features as part of channel maintenance. Unfortunately this may not always produce the hoped-for reduction in hydraulic resistance and, even if there is a benefit, it may only be temporary as the bed features may rapidly reform. The issue of whether to carry out maintenance and what the resulting benefits would be, therefore, is complicated.

In general, maintenance work should be minimised. This not only saves money but also results in the minimum environmental impact on the river eco-system.

2.3.2 Identification of maintenance requirement

It is important to establish whether there is a need for maintenance and if so what is the most appropriate form that maintenance work should take. In many natural, stable river systems no maintenance is required to pass large floods. If engineering work has been carried out in the past or where there are constraints on flooding and flood levels then maintenance work may well be required.

In designing future schemes the level and nature of maintenance required should be fully investigated as part of the design process.

For channels where there is an existing problem it is important to establish the cause of the problem. If this is not done then there is a danger that the symptom is treated rather than the cause. It is necessary to consider what work is required, where and how frequently. In analysing particular problems it must be remembered that the problems observed at one location may have their origin at another location upstream or downstream. Particularly for sediment problems it may be necessary to use a catchment-wide approach to establish the true nature and cause of a problem.

Sear and Newson (1993) have developed a standard procedure for evaluating sediment-related problems, which has the potential for linking cause and effect.

In considering maintenance work it is important to take account of the natural processes in a river. The removal of a naturally formed sediment shoal may appear to be attractive but if it reforms during the next flood it is unlikely to be hydraulically or cost effective.

As described in Section 2.2 on Design above, any flood defence scheme which increases the conveyance of a channel is likely to lead to sediment related problems. If the sediment problem is small then this may be an acceptable consequence of the scheme but if the sediment problem is large then this may invalidate the economics of the scheme or, in extreme cases, render the complete scheme ineffective. For example, channel widening which leads to sediment deposition so that maintenance work has to be carried out every ten or twenty years may be acceptable. In this case the maintenance cost may be an acceptable price to pay for the flood defence benefit provided. If maintenance work is required every year or after every flood then the maintenance work may not be justified and another option should be considered. It is important, therefore, to estimate the requirement for, and impact of, maintenance work.

The impact of any maintenance work that acts to reverse some natural process, for example dredging in an area of sediment deposition, is only likely to have a temporary effect. The sustainability of such work depends crucially on the rate of the process involved. It is necessary, therefore, to assess the consequences of maintenance work.

Table 2.3 Potential impact of maintenance work

Type of works	Potential impact
Dredging	Bank failure; increased rate of sediment deposition
Removal of bed features	Bank failure; reformation of bed features
Plan form change	Return to original plan form accompanied by bank erosion and failure

The specification of maintenance work should take account of the fundamental sediment processes. Let us take dredging as an example. The processes of sediment movement around bends means that in natural channels the depth across a cross-section taken at the bend is not uniform. If a uniform cross-section profile is created by dredging then natural sediment movement during a subsequent flood will re-work the sediment and modify the cross-section shape. This may nullify the impact of the dredging. If the dredging were designed to take account of the natural processes and provide the appropriate depth variation across the channel then such subsequent changes would not take place.

The environmental impact of maintenance work should also be considered. If dredging is required, it may be less disruptive to the flora and fauna if the dredging is confined to only part of the width of the channel. The selection of areas to be dredged and those to be left can be based on geomorphological principles.

3 Concepts and Definitions

3.1 Introduction

This chapter deals with concepts and definitions, starting with the broader aspects of catchment erosion and deposition and then moving to more detailed aspects concerning the nature of sediments and sediment processes.

To progress beyond the merely descriptive it is necessary to develop predictive theories for sediment processes. If one has such theories then one can make predictions of the future consequences of proposed actions. Theories for sediment transport in rivers date back more than 100 years but until recently were notorious for the differences between predicted and observed sediment behaviour. Through time the theories have become more complex. Any sediment theory contains an empirical element and over time the amount of data that is available to calibrate such theories has increased. These two trends have lead to improvements in their predictive capability. Over the last 30 years there appears to have been little overall improvement in the predictive behaviour of the theories and it is tempting to speculate that some limit has been reached, either in the nature of the theoretic approach that has been adopted or in the accuracy of the available data.

It had long been observed that there is some threshold flow condition below which sediment does not move. Shields did pioneering work in characterising this flow condition for ‘initiation of motion’. These threshold conditions have since often been incorporated into sediment transport theories in one way or another.

Over the last 50 years our knowledge of turbulence has been increasing. With ever more refined measurement techniques it is now possible to investigate in greater detail the links between turbulence and sediment movement.

Factors which influence sediment transport include:

- flow conditions
- sediment size and
- sediment density.

Methods to predict sediment transport rates are discussed in greater detail in Chapter 6 and Appendix 2.

There is an interaction between the movement of sediment and the flow. The flow determines the sediment transport but the movement of sediment controls the size and shape of bed forms which in turn affects the hydraulic resistance and hence the flow. In order to calculate the capacity of a particular channel, or the depth of flow for a particular discharge, it is necessary to define and understand what determines the resistance to flow.

Factors which influence the resistance of a channel include:-

- Surface roughness, including the roughness associated with the sediment grains (grain roughness) and the roughness associated bed forms (form roughness).
- Vegetation, which may vary seasonally,
- Variations in the cross-section of the channel in the direction of flow.
- Variations in channel alignment.
- Variations in longitudinal slope, for example, pools and riffles in gravel bed rivers.
- General bed topography as affected by sediment deposition and erosion.
- Obstructions, natural or man made, within the channel.

The overall resistance of a channel will usually arise from a combination of several of the factors given above.

In this manual we cover the topic of alluvial resistance, that is, the resistance which is directly attributable to the sediments within the channel. Other sources of resistance, such as vegetation, channel shape and alignment are not dealt with in detail but these other aspects are considered in Chow (1959), Barnes (1967), Hicks and Mason (1991) and Fisher (1996). The alluvial resistance is the dominant factor in determining the overall resistance of channels in which the mobile sediment bed is a large proportion of the overall wetted perimeter, as in wide rivers, or for narrower channels with mobile beds in which the banks do not contribute significantly to the overall roughness. Thus alluvial resistance is the dominant factor in the overall resistance for the following types of channel:-

- Gravel rivers where the width to depth ratio is high, say > 10.
- Large sand bed rivers where the width to depth ratio is high, say > 10.
- Well maintained canals with steep or vertical banks.
- Laboratory flumes with mobile beds.

An important aspect of alluvial resistance is the way that it varies with flow conditions. As flow conditions vary the size and shape of bed features may change leading to significant variation in hydraulic roughness. For fixed roughness elements it is commonly found that, due to the variation of Manning's n with depth, the effective roughness reduces with increasing discharge. In alluvial channels an increase in discharge may lead to an increase in the size and shape of bed features. This change in the bed features may lead to increased form losses and hence increased roughness. Thus in alluvial channels it is quite possible for the hydraulic roughness to increase substantially with discharge, in contrast to the normal behaviour of fixed-bed roughness elements. This type of behaviour is by no means universal; for some flow conditions bed features may reduce in size with increasing discharge. This reduces form losses and leads to more rapid reductions in hydraulic roughness than one would expect for fixed-bed channels. In situations where a component of the hydraulic roughness arises from alluvial resistance it is important, therefore, to be able to predict the variation of alluvial resistance with flow conditions.

Early empirical approaches to the subject of channel resistance were concerned with field observations and the interpretation of those field results using simple equations derived from the data. Chezy (1768) and Manning (1895) were the main proponents of this type of approach. Their data was relatively restricted and others have sought to make the techniques more universally applicable by relating the basic empirical parameters (Chezy "C" and Manning "n") to observable characteristics of channels. Amongst these are Chow (1959), Barnes (1967), Hicks and Mason (1991) and Hollinrake and Fisher (1995).

In the 1930s there was a quantum leap in our understanding of turbulence and a new framework for explaining and determining resistance was developed. It was first applied to smooth pipes by Nikuradse (1933) and then extended to include rough pipes by Colebrook and White (1937 and 1939). The new framework, founded on a sound understanding of turbulence, is a powerful tool that is more universally applicable than the simple, earlier approaches. Ackers (1958) extended the Colebrook and White approach to cover open channels as well as pipes and demonstrated the correlation between the Manning approach and the Colebrook and White approach in the fully developed rough turbulent range of flow conditions. He also pointed out the hazards of using the Manning approach in anything other than the fully developed turbulent range of flow. Ackers developed graphical and tabular solutions for the Colebrook and White equations and the most recent set of Tables to include these is by HR Wallingford and Barr (1998).

The methods of predicting channel resistance are described in Chapter 8 and Appendix 4. A brief description is given of the early empirical approaches because these remain in common usage. A more comprehensive description is given of the modern approach to channel resistance with particular attention being paid to the alluvial resistance component of the overall resistance.

3.2 Erosion and Deposition

Erosion is the detachment of soil and rock fragments from their original resting place by water, ice, wind, volcanoes, earthquakes, etc. Erosion has been categorised into three main types:

Geological erosion: Mainly associated with upland regions and caused by volcanic eruptions, earthquakes, landslides, mudflows and gullying. It is responsible for creating major changes to land topography.

Soil erosion: Mainly associated with agricultural regions and caused by the impact of rainfall on land surfaces and/or surface run-off. It is responsible for sheet erosion and the development of rill and gully formations.

Water course erosion: Erosion of the bed and/or banks of streams by running water.

Deposition of sediment: Net deposition mainly occurs in the lower reaches of river systems. Deposition of sediments forms floodplains and is often temporary, pending further reworking by the river system.

This manual is concerned with water courses which receive sediments produced by geological or soil erosion processes. The amount of sediment transported by a water course depends on a number of factors which are explained more fully in Chapter 6. Erosion or deposition takes place if the spatial derivative of the sediment transport rate is non-zero. Erosion is associated with an increase in sediment transport rate in the flow direction and deposition is associated with a decrease in sediment transport rate in the flow direction. Erosion can, for example, be caused by low sediment inflow into a reach while sediment deposition can similarly be caused by high sediment inflow to a reach.

3.3 Catchment Characteristics

The movement of sediments within river basins is dependent, on a broad scale, upon many catchment characteristics. These characteristics may be physical or hydrological while, in nature, these are strongly inter-related.

Physical characteristics: Topography, geology, soils, vegetation, land use practices and water course development all affect the erosion, transport and deposition of sediments. Physical disturbances such as earthquakes, avalanches, volcanic eruptions, mudflows and landslides may also have a significant influence.

Hydrological characteristics: Precipitation, both quantity and intensity, and temperature are important in the development of vegetation cover. Precipitation and run-off play a key role in the erosion, transport and deposition of sediment.

Sediment yields: The sediment yield from a catchment varies with a number of relevant variables including the catchment size and the volume of runoff. In general the catchment size is an important variable. Smaller catchments usually have higher sediment yields per unit area than larger catchments in the same locality. For catchments with similar areas, the sediment yield will vary with topography and rainfall quantity and intensity.

The sediment yield for a particular catchment will also vary from year to year. This may be due to variations in rainfall or snow cover or it may be due to events that occur within a catchment. Thus a local landslide may introduce an unusual amount of sediment into the fluvial system. Over a period of years, however, the system will return towards more normal conditions until it is perturbed by another such event.
The natural variability described above makes the interpretation of sediment yield data from a catchment difficult. However there is a general trend for sediment yields per unit area to decrease as the catchment size increases, see Figure 3.1.

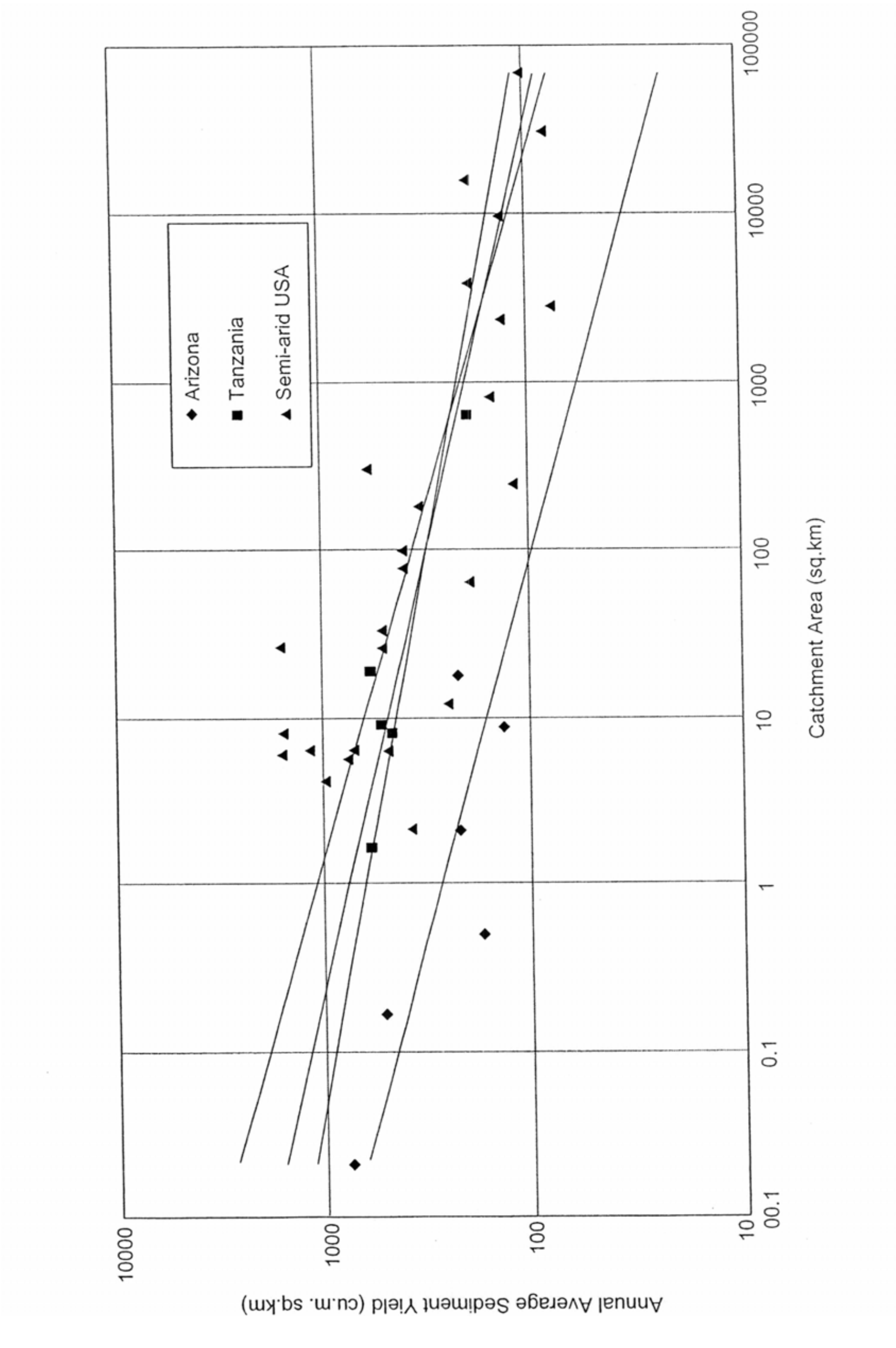
A detailed discussion of the sediment yield from a catchment is beyond the scope of this text but the reader is referred to texts such as Bogen et al (1992) and Hudson (1993).

3.4 Sediment characteristics

3.4.1 Non-cohesive and cohesive particles

Sediments can be divided into cohesive and non-cohesive categories. When resting on the bed or banks of a water course cohesive sediments are held together by electrostatic/chemical bonds which resist erosive forces. Once in motion, however, they lose this bond to a certain extent. The size of cohesive sediments is generally less than approximately 0.06 mm but this figure may vary depending upon the chemical composition of the sediment. For larger sediments the cohesive forces become less significant than the gravitational forces. Non-cohesive sediments consist of larger particles, the movements of which are determined by the physical characteristics of the particles and the imposed hydrodynamic forces. Both types of sediments are found in natural water courses with a predominance of coarse, non-cohesive sediments in upland rivers and a predominance of fine, cohesive sediments in the lower reaches.

Figure 3.1 Sediment yields vs catchment area



3.4.2 Particle size

Particle size is an important factor in determining the transportability of sediment. Sizes range from upwards of 2 m equivalent diameter in mountain streams to less than 0.0005 mm in sluggish lowland rivers. The former travel predominantly along or close to the bed (bed load) and the latter remain almost indefinitely in suspension in the flow (suspended load), see later for a discussion of modes of sediment transport. The following dimensions are often used to describe particle size:

Sieve diameter: The size of sieve opening through which the particle will pass. Commonly used for sizes between 0.1 mm and 75 mm.

Equivalent diameter: The diameter of a sphere of the same density that would exhibit the same fall velocity as the particle in a given fluid at the same temperature. Commonly used for sizes less than 0.1 mm.

Nominal diameter: The diameter of a sphere of the same volume as the particle. Used for sizes in excess of 75 mm.

Triaxial dimension: Three dimensions which are mutually at right angles. The planes are chosen to include both the maximum and minimum dimensions of the particle. Used for sizes in excess of 75 mm.

Natural sediments exhibit a range of sediment sizes that can be displayed as a cumulative frequency curve. Figure 3.2 shows sediment grading for a range of materials of differing average size. There is a general tendency for the range of sizes to increase as the mean size increases and this has implications in the way in which sediment transport rates are calculated; see later.

Naturally occurring sediments are often irregular in shape and the hence the definition of “size” in terms of a single length dimension can, under some circumstances, be an unacceptable simplification.

3.4.3 Particle shape

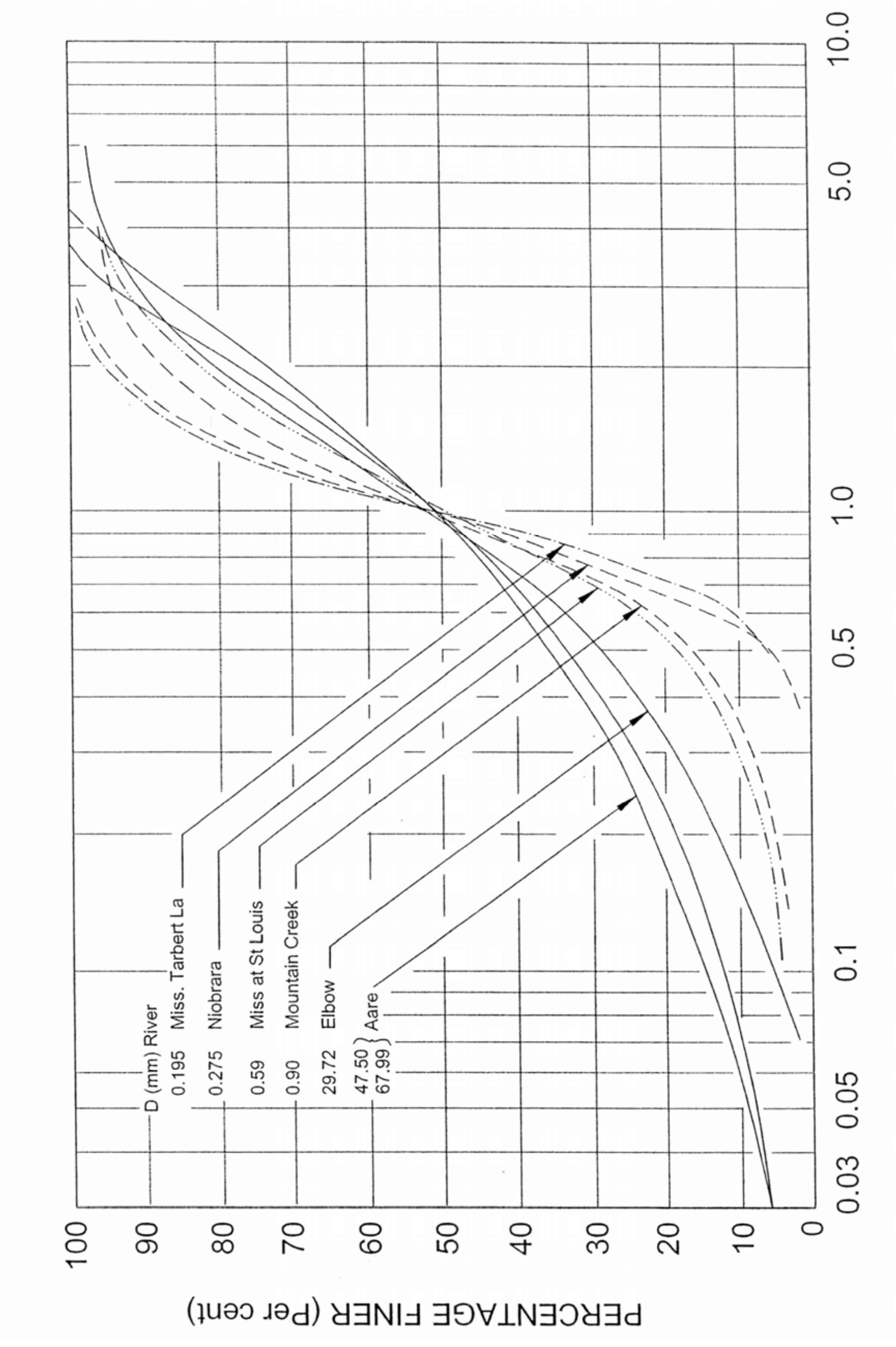
Particle shape influences transportability. Flat shale particles lie on the bed of a water course in such a way as to minimise the resistance to flow. They experience smaller shear forces than round particles of the same weight and their movement characteristics are not the same. Particle shape may be defined in many ways:

Surface, volume ratio: The ratio of the surface area of the particle to the surface area of a sphere of equal volume.

Sphericity: The cube root of the ratio of the volume of the particle to the volume of its circumscribing sphere.

Roundness: The average radius of curvature of the individual edges to the radius of the largest circle which can be inscribed within the cross-section of the particle.

Figure 3.2 Dimensionless grain size composition



3.4.4 Particle density

The movement of sediment is driven by tractive hydrodynamic forces and resisted, among other things, by the weight of the particle. The tractive forces depend on the size and shape of the particle and the weight depends on size and density. Hence density has an important effect on sediment movement. Natural sediments have a specific gravity (weight relative to water for a given volume) which varies from just over 1.0 to 2.7 depending upon their mineral composition. Most commonly occurring sediments have a density of approximately 2.65. The variation in tractive force required to move particles as a result of variations in particle size and density can lead to flow segregating different particle types and gives rise to effects such as preferential erosion and/or deposition.

In some problems it is necessary to consider the bulk density of sediments as opposed to the density of individual particles. Newly deposited sediment can, for example, exhibit a high proportion of voids between the particles and is more prone to erosion than more densely packed material. This is particularly relevant when considering reservoir sedimentation. Fine silts and clays will have a low density when first deposited but will gradually self-consolidate with the passage of time and the deposition of additional sediment on top of them. Thus the density of the sediment bed becomes a function of time and also varies with depth.

3.4.5 Fall velocity

The particle fall velocity is the steady velocity that is reached by a particle falling through water. The normal approach is to measure the fall velocity in still water. Particle fall velocity is frequently used in predictive techniques for assessing sediment movement. It is a fundamental property of the sediment/water system which depends on the size, shape and density of the particle and the density and viscosity of the water. Figure 3.3 shows how fall velocity varies with particle size.

3.5 Bed features

Bed features are always present in alluvial channels and are inextricably related to both the resistance of the channel to flowing water and the transport of sediments within the channel. Water courses exhibit a range of bed features (forms) as follows:

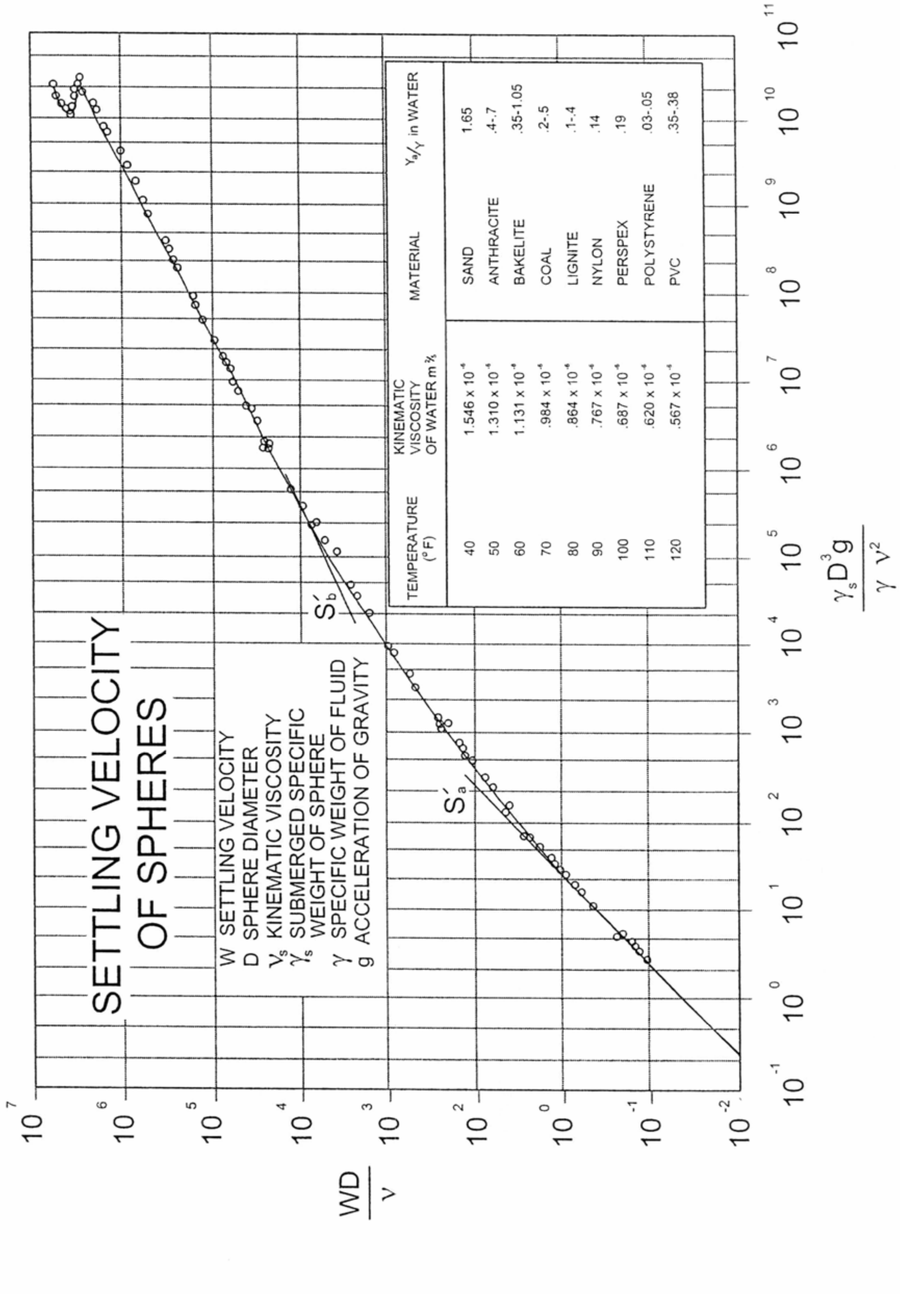


Figure 3.3 Settling velocity of spheres

Plain bed: This is the condition where the bed, measured over a wide area, is sensibly a plane surface. This does not mean that the bed is hydraulically smooth, however, the sediment forming the bed exhibits a grain roughness associated with the size of individual particles. Plain beds, see Figure 3.4, can occur when there is no movement of sediment and under specific circumstances when there is rapid movement of the grains.

Ripples: Ripples take the form of undulations on the bed of the channel of the type shown in Figure 3.4. Ripples are usually three-dimensional and rarely occupy more than 20 per cent of the flow depth. They tend to occur at low transport rates and with particles at the fine end of the non-cohesive range. Individual particles move in more or less continuous contact with the bed by rolling over the crest of the ripples and coming to rest on the downstream face. They are then covered by the advancing ripple to be re-activated sometime later when they re-emerge on the upstream face.

Dunes: Dunes tend to be larger than ripples and their longitudinal profile is asymmetrical, see Figure 3.4. They are more two-dimensional in that they exhibit crests across the stream and they can occupy a significant proportion of the depth. Movement is downstream and results from sediment toppling over the crest of the dune and settling on the downstream face.

Transitional: At higher flow rates dunes tend to wash out and the bed of the channel undergoes a series of complex mutations. Sand bars, sand waves, washed out dunes and plane bed have all been observed in this rather ill-defined category.

Antidunes: Antidunes, see Figure 3.4, take the form of a train of symmetrical sand waves which are in phase with a corresponding series of water surface waves. Both trains move steadily upstream although individual sediment particles move rapidly downstream. The sand and water waves increase in height until they break. This causes a sudden reduction in height which is then regained shortly afterwards.

Full descriptions of the topic of bed features are given in the following references; Simons and Richardson (1960 and 1961), Raudkivi (1967), Kennedy (1969), Graf (1971), Yalin (1972 and 1992), Znamenskaja (1976) and Bettess and White (1998).

3.6 Transport Characteristics

3.6.1 Threshold of movement

As the flow of water over a bed of loose granular sediment increases, a point is reached where a few grains are dislodged by the flow and move a small distance in the direction of the flow. This condition, although it is hard to define in an exact manner, is known as the threshold of movement or the initiation of motion, see Chapter 5.

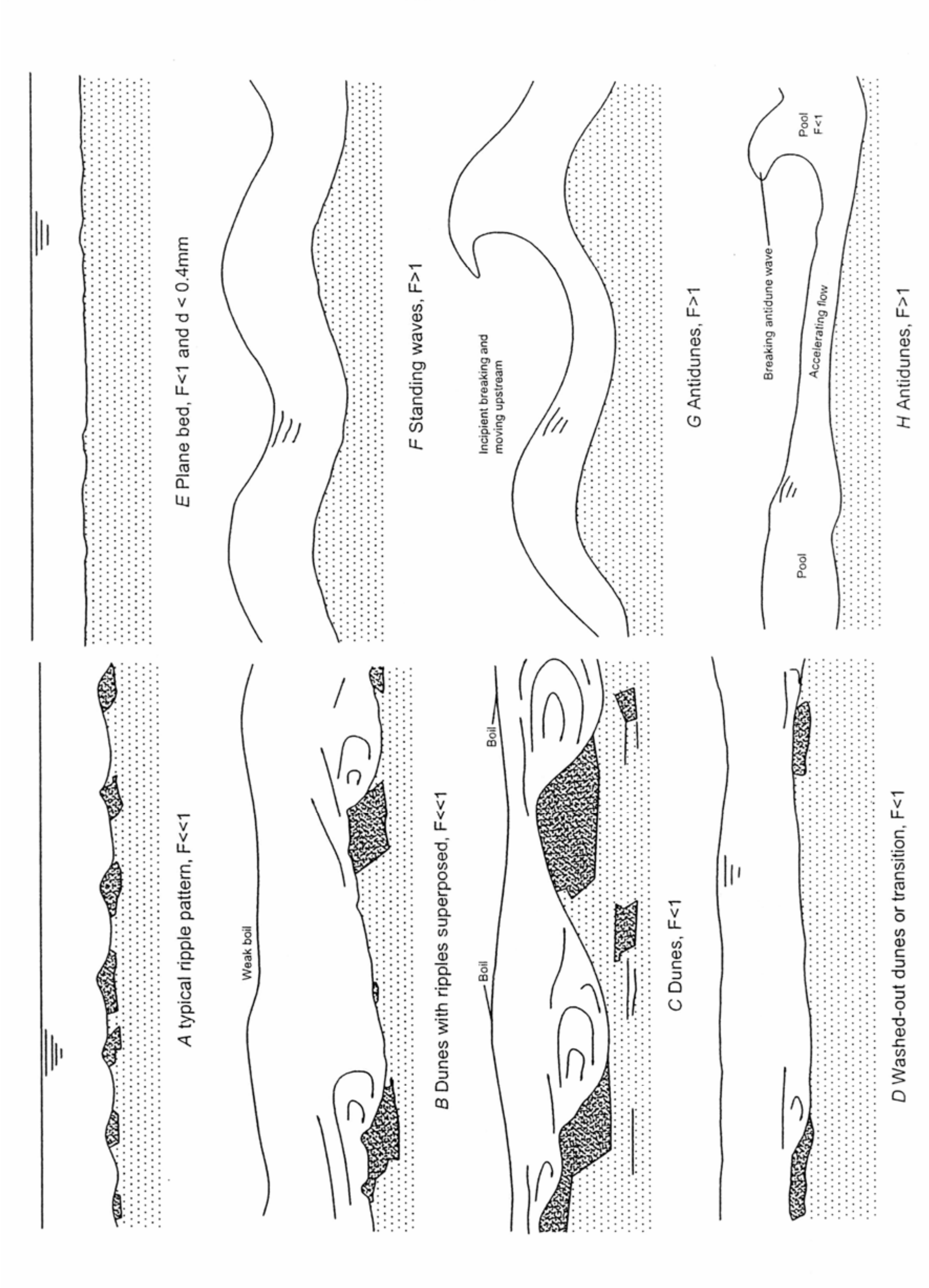


Figure 3.4 Idealised bed forms in alluvial channels

3.6.2 Bed load

Increases in the hydrodynamic forces over and above those necessary to create incipient motion cause movement of bed material in the direction of flow. Individual particles move along the bed of the water course by rolling, sliding or occasionally in jumps, (saltation). The direction of motion is generally parallel with the flow and vertical accelerations are minimal. Those particles in motion close to the bed at any particular instant in time constitute the bed load.

A rigorous definition of bed load has proved illusive but Einstein (1950) has provided a list of features commonly ascribed to the phenomenon:

- There is a steady and intensive exchange of particles between the moving bed load and the bed.
- The bed load moves slowly downstream and the motion of an individual particle is one of quick steps with comparatively long intermediate rest periods.
- The average step length is largely independent of the flow condition and the transport rate.
- Different bed load transport rates are achieved by the particles moving more or less often.

Engineers, environmentalists and others are concerned with the rate of transport of the bed load and numerous predictive techniques for doing this have been developed over the last 100 years or so. The following references cover the subject; Du Boys (1879), Kalinski (1947), Meyer-Peter and Muller (1948), Einstein (1950), Bagnold (1956), Rottner (1959), Goncharov (1962), Raudkivi (1967), Graf (1971), White (1972), Bogardi (1974), White, Milli and Crabbe (1975).

3.6.3 Suspended bed material load

As the rate of flow in a water course increases the depths, velocities and turbulent intensities also increase. The stage is finally reached where the fluctuating lift forces generated by the turbulence generally exceed the weight of the particles. Accordingly the particles no longer follow a well defined trajectory, instead they follow random paths within the fluid. These random paths occasionally redeposit particles on the bed and hence individual particles may, at different times, constitute part of the bed load and part of the suspended bed material load. Thus the distinction between the bed load and the suspended bed material load (often abbreviated to the suspended load) is difficult to make in a scientific sense. It does provide, however, a practical classification which is of value to river engineers and environmentalists.

When flow conditions are such that the incipient motion condition has not been reached both the bed load and the suspended load are zero. At flows just above the incipient motion condition transport is mainly as bed load and the suspended bed material load is small. During flood events in sand bed rivers, transport is mainly as suspended bed material load which can exceed the bed load by a factor of 10 or so.

The division between bed load and suspended load is artificial. In reality there is a continuum of behaviour going from bed load at one extreme to suspended load at the other. The division between bed load and suspended load depends upon both the sediment size and the flow. Thus a particular sediment size may behave as bed load under one flow condition and as suspended load under another flow condition.

3.6.4 Total bed material load

For practical purposes it is useful to be able to calculate the total transport of bed material since this quantity is of direct relevance in determining such things as sedimentation in reservoirs and erosion and deposition in water courses. The total transport of bed material has also been shown to be of direct relevance to the shape, size and slope of equilibrium alluvial channels.

Many predictive techniques have been developed for the determination of total bed material transport. These techniques calculate the sum of the bed load and the suspended bed material load and do not indicate the proportions of each. The following references cover the subject; Einstein (1950), Laursen (1958), Bishop, Simons and Richardson (1965), Bagnold (1966), Engelund and Hansen (1967), Graf (1971), Toffaleti (1969), Ackers and White (1972), Van Rijn (1984), Garde and Ranga Raju (1985) and Yalin (1992).

3.6.5 Wash Load (fine material load)

Very small particles are either stationary on the bed of a water course or travel more or less permanently in suspension, see Figure 3.5. Bed load movement by saltation is not possible for these fine materials. A precise value of size at which this phenomenon occurs is hard to define but generally it is within the range 0.06 mm to 0.10 mm and corresponds approximately to the divide between cohesive and non-cohesive materials. As in the division between bed load and suspended load the division between suspended load and wash load is an arbitrary division of a continuum of behaviour. Again the division also depends upon both the sediment size and the flow conditions. Thus a particular sediment size may behave as wash load under one flow condition and as suspended load under another.

These fine materials constitute the wash load and individual particles travel at a velocity approaching the local water velocity. The amount of fine material in suspension is not governed directly by the local hydraulic conditions. It is almost entirely dependent upon the amount of fine material entering the reach under consideration and the availability of erodible material in the reach. This is the fundamental difference between the wash load and the suspended bed material load.

Predictive techniques to determine the magnitude of the wash load are, at best, very approximate and are based on field observations of soil losses from catchments. For specific projects, in-river measurements of the wash load are made, preferably over an extended period of time, and a rough correlation between flow and wash load is obtained. This is clearly not a unique relationship and the data always exhibits a large amount of scatter.

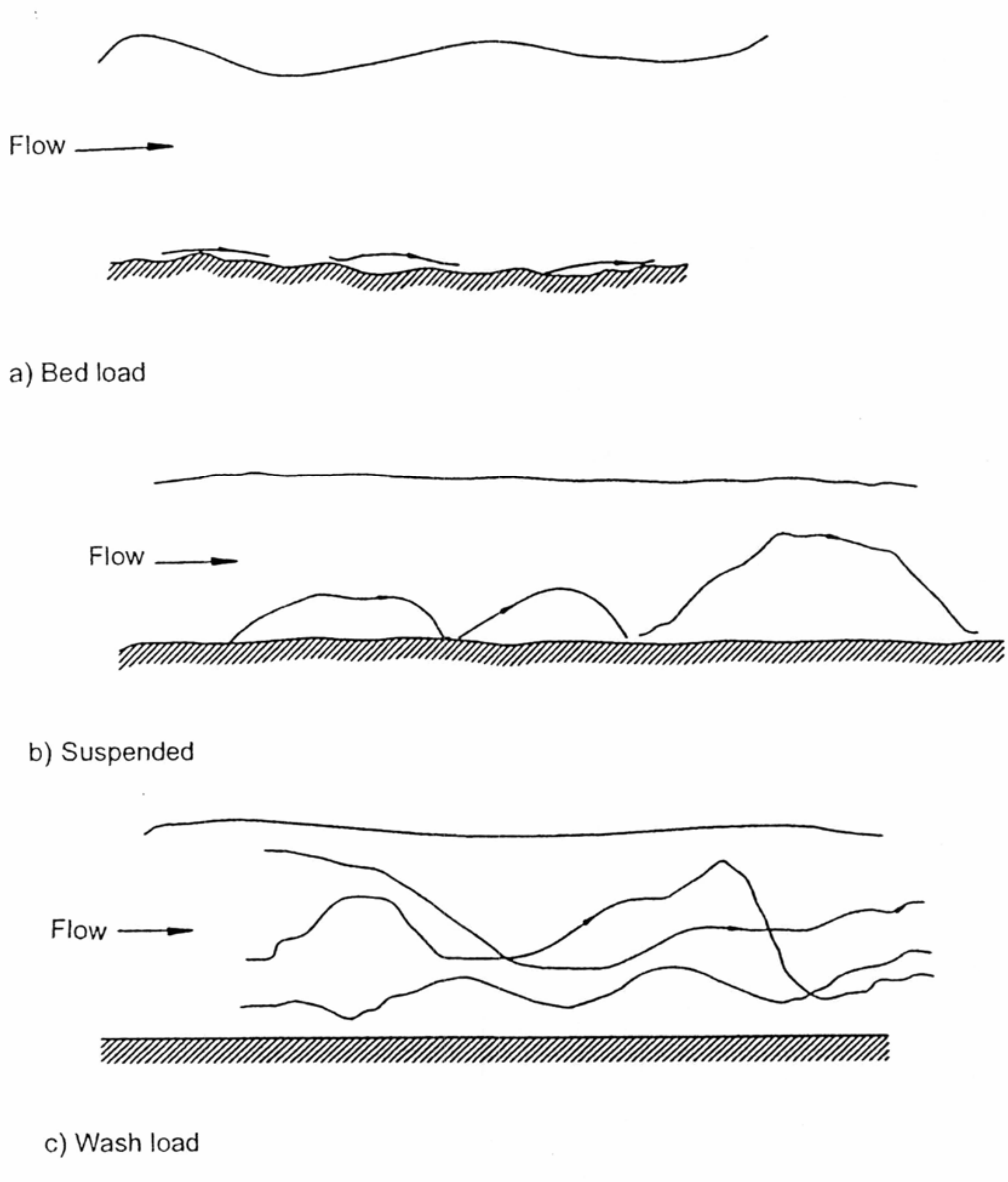


Figure 3.5 Typical sediment particle trajectories

3.7 Division between Bed Load and Suspended load

Julien (1994) describes a study to look at the ratio of suspended load to total load as a function of the ratio of shear velocity to fall velocity, (v_*/ω). The shear velocity is a measure of the hydrodynamic forces while the fall velocity is a measure of the gravitational force on the sediment. It can be seen in Figure 3.6 that in most practical situations, if v_*/ω <1 then the predominant mode of motion is bed load. If v_*/ω >2 then suspended load dominates.

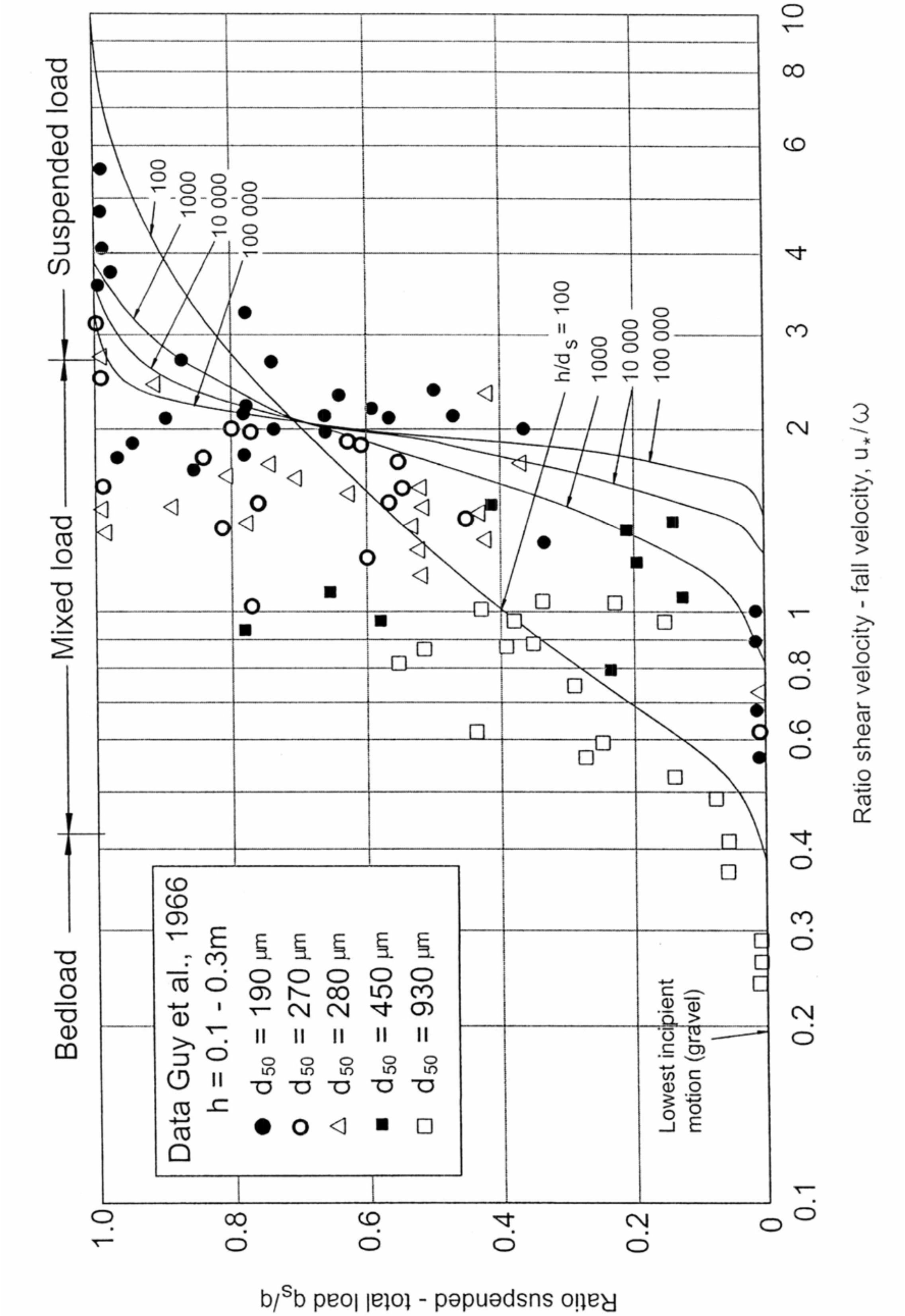
It should be noted that the above analysis applies to one single sediment size. If the bed sediment contains a range of sediment sizes then the picture is a little more complicated. It is not sufficient just to look at the composition of the bed and determine the mode appropriate to the majority of the bed material. We can illustrate this using an example.

For steady flow it is possible to determine theoretically the vertical concentration profile. The form of the profile depends upon the Rouse number defined by $\omega/(\kappa v_*)$, where

ω is the fall velocity of the sediment,
κ is von Karman's constant and
v_* is the shear velocity.

see Figure 3.7. For small values of the Rouse number the sediment concentration becomes increasingly uniform through the depth, that is, the sediment behaves increasingly as wash load. For large values of the Rouse number the sediment becomes increasingly concentrated towards the bed, that is, the sediment behaves increasingly as bed load.

Figure 3.6 Ratio of suspended load versus ratio of shear stress to fall velocity



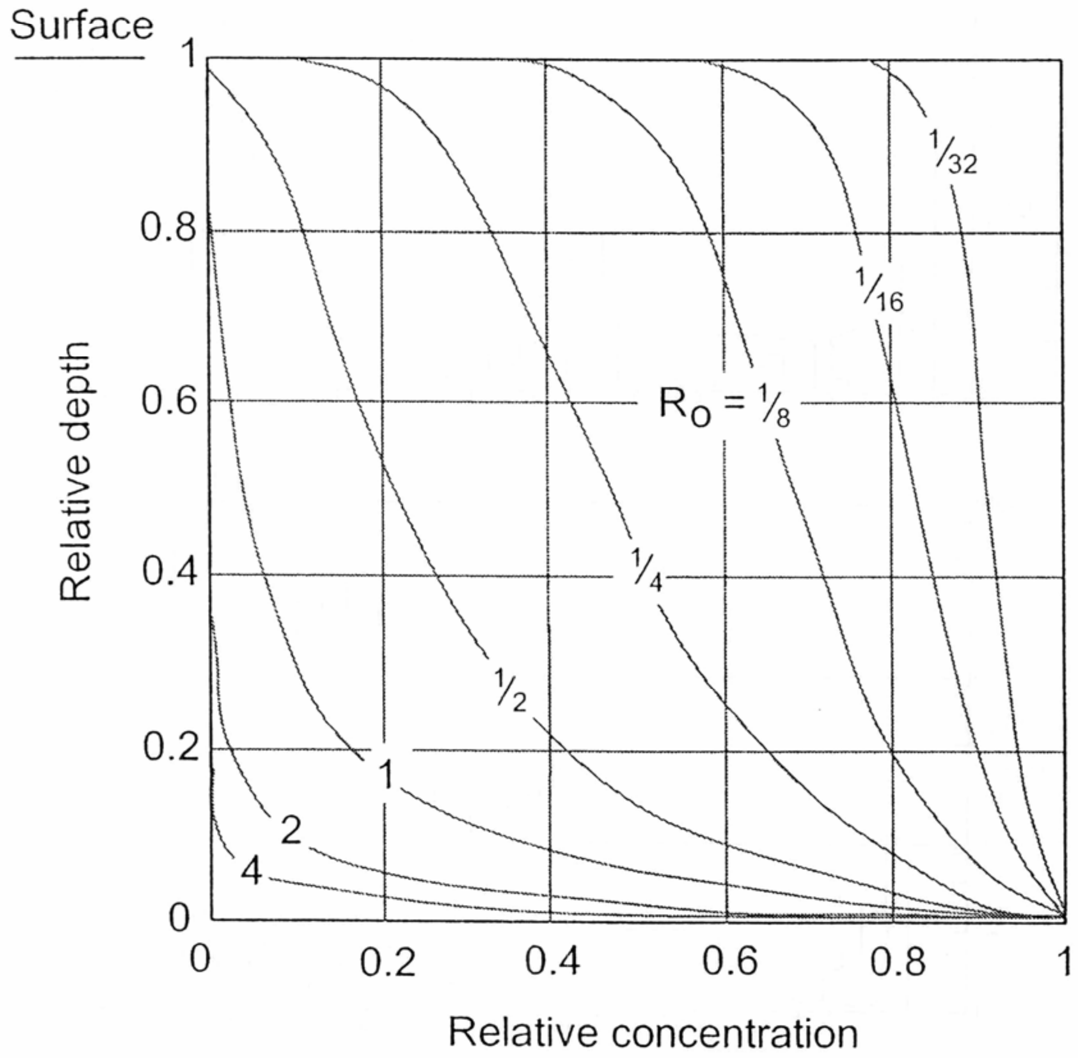


Figure 3.7 Equilibrium suspended sediment concentration profiles

Example to illustrate the impact of sediment size on sediment transport rate

Suppose we have a sediment with the following grading:

	D_{10}	D_{30}	D_{50}	D_{70}	D_{90}
Size (mm)	0.065	0.1	0.2	0.5	1.0

We will now assume a flow such that the shear velocity is twice the fall velocity for the D_{50} size. Thus approximately half the sediment sizes on the bed will move as bed load and half as suspended load. We can now use the Ackers and White sediment transport theory to calculate the sediment concentrations for each sediment size.

Sediment	D_{10}	D_{30}	D_{50}	D_{70}	D_{90}
Conc (ppm)	24.2	4.8	1.6	0.6	0

If we assume that everything up to and including the D_{50} size is moving as bed load and everything larger is moving as suspended load we can see that the suspended load (4.8 + 24.2 = 29 ppm) significantly exceeds the bed load (0.6 + 1.6 = 2.2 ppm). Thus though half the sediment on the bed is moving as bed load, because the suspended load is moving at higher concentrations the dominant mode of sediment movement is suspended load. To ensure that the amount of sediment moving as bed load was approximately equal to that moving as suspended load the proportions of the different sediment sizes would have to be approximately:

	D_2	D_4	D_{23}	D_{53}	D_{83}
Size (mm)	0.065	0.1	0.2	0.5	1.0

that is, the sediment moving as suspended load contributes over half the sediment load but comprises only approximately 8% of the sediment on the bed of the channel.

This shows that the fine sediment may only be a small percentage of that present on the bed but it may dominate the total sediment transport because of the different mobilities of fine and coarse sediments.

The above calculations demonstrate how the sediment transport rate is sensitive to sediment size. It also illustrates how important it is to have an accurate bed sediment grading curve when carrying out sediment transport calculations.

3.8 Sediment Transport and Floods

Sediment transport is very sensitive to flow conditions and increases dramatically during floods. Figure 3.8 shows the flow and sediment discharge as a function of time during a flood. It can be seen that while the flow increases by a factor of approximately 15, the sediment transport rate increases almost a thousand fold. Figure 3.9 also shows the same degree of sensitivity to flow. Figure 3.9 also shows two grading curves for sediment samples taken at different discharges. It can be seen that the composition of the sediment in motion changes significantly as the discharge changes. As the discharge increases the sediment in motion becomes coarser.

Figure 3.8 Flow and sediment concentration as a function to time during a flood

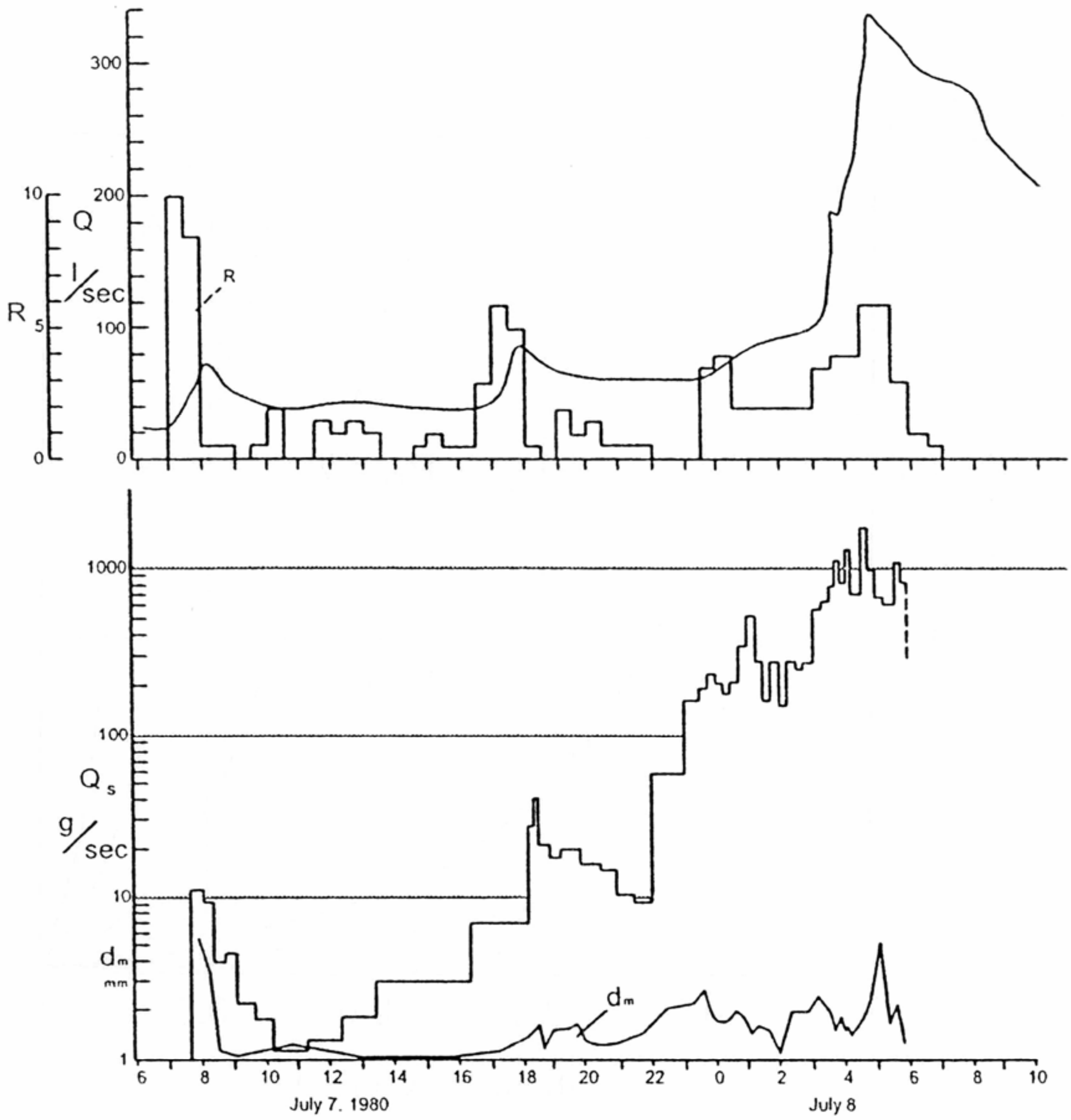


Figure 3.9 Composition of sediment in motion for two different discharges

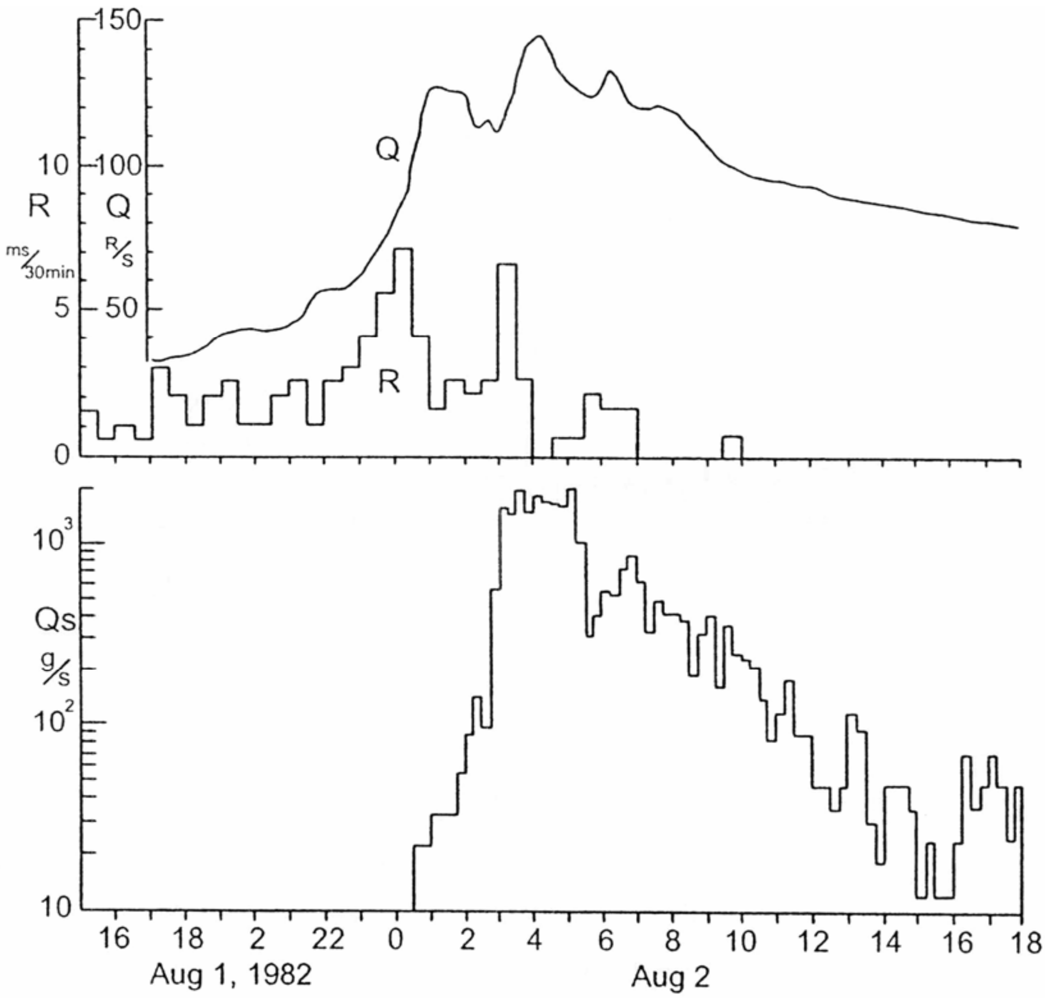


Figure 3.10 Variation of sediment concentration during a flood

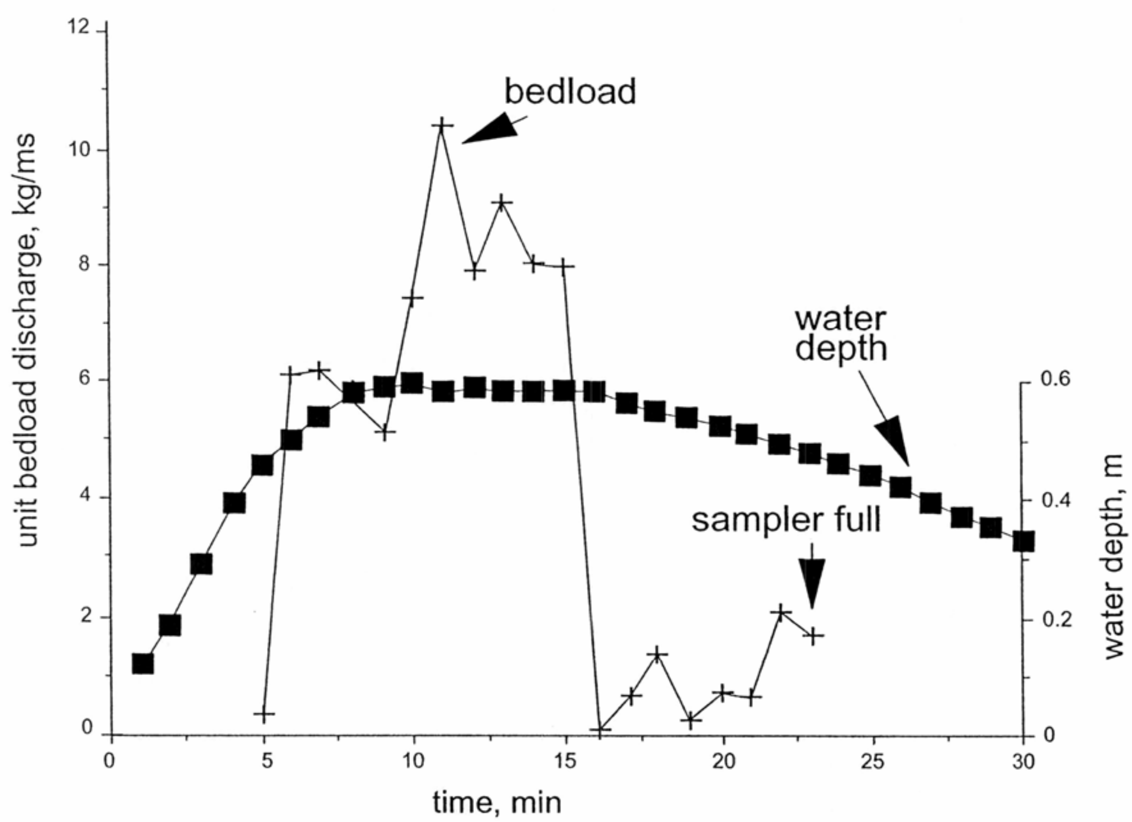


Figure 3.10 shows that the sediment transport rate may vary on a time scale shorter than the duration of the flood. Thus sediment movement may not take place during the entire flood period but may be confined to only part of it.

One consequence of the sensitivity of sediment transport to flow is that the bulk of sediment transport occurs during floods and that during the inter-flood periods there may be little sediment movement, see Figure 3.11. It can be seen that significant quantities of sediment are moved only during a few events in the year. For the rest of the year sediment transport rates are small. Thus in determining the total annual sediment transport rate it is important to concentrate on the large flood events and that less attention can be paid to low flow periods. The sensitivity to the large flood events means that there may be quite large differences in the annual sediment load from year to year depending upon the number and size of the largest flood events. A number of years may have to be considered before one can determine the mean annual sediment load. Having determined such a mean value the actual sediment load in a particular year may differ from it quite markedly.

3.9 Bed Forms

3.9.1 Introduction

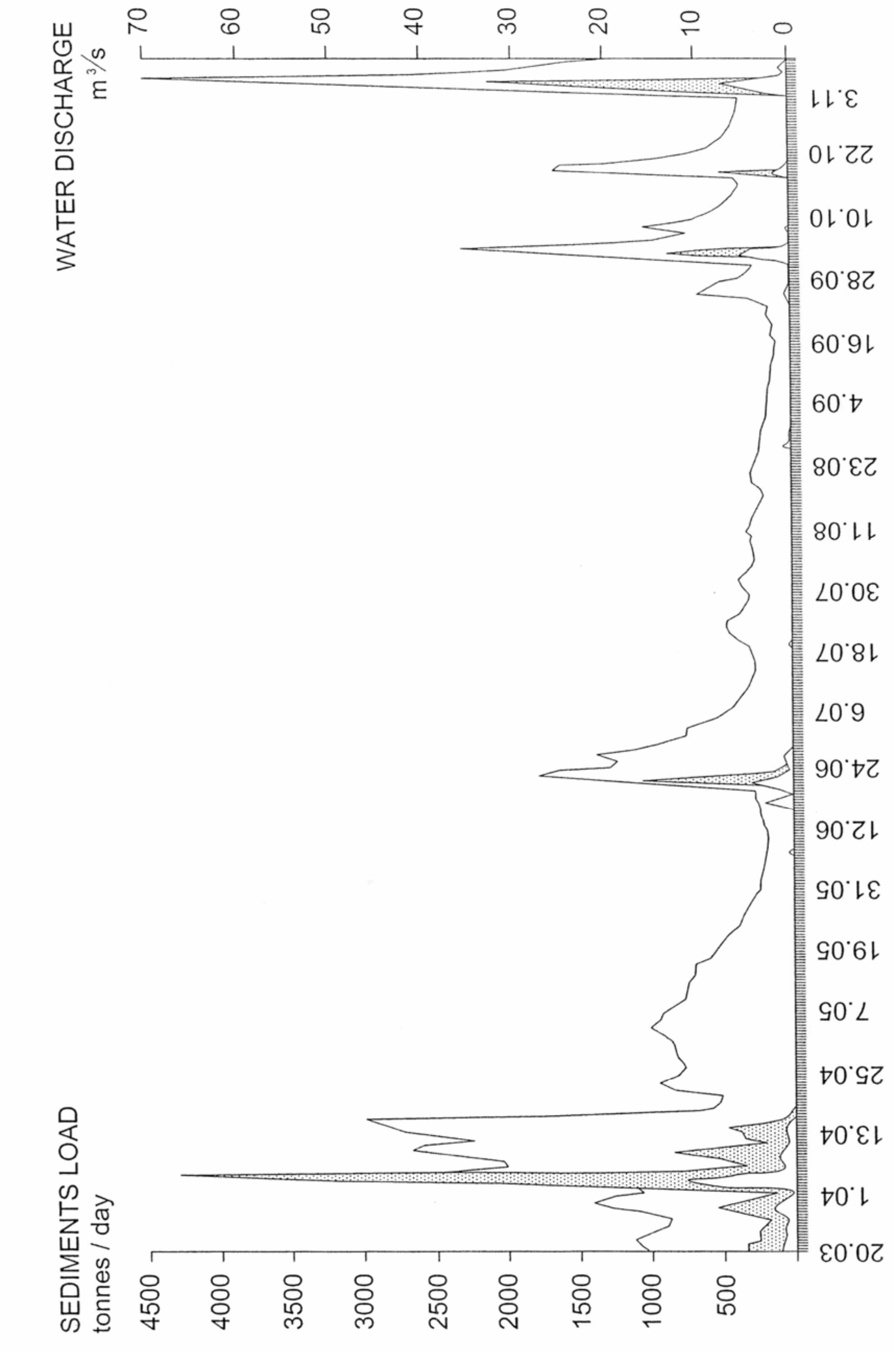
Bed forms occur on differing spatial scales ranging from tens of millimetres to thousands of metres, with the different scales of bed forms having different properties. The physical mechanisms responsible for the formation of such bed forms are not completely understood but, presumably, different physical mechanisms are involved for the different spatial scales.

Definitions of the various bed forms are given below in Section 3.11. As was indicated above, bed forms arise from a range of physical mechanisms and, as a result, behave in a variety of different ways. Unfortunately the terminology that has developed does not always distinguish precisely the different possible types of behaviour. Perhaps the most obvious example is of the use of the term ‘bars’. This can be used, as in alternate bars, to describe a system that is mobile and progresses downstream, or, as in point bars, to describe stationary features determined by the channel plan form geometry, or to describe transitory features which appear and disappear in braided rivers. Thus unfortunately the term ‘bar’ does not give a precise indication of the nature of the bed feature alluded to.

*Ripples:*Ripples are small bed forms that are usually less than 0.3m long, in the direction of flow, and less than 0.03m in height. In longitudinal section, ripples vary from triangular to sinusoidal in shape and their size is not dependent upon flow depth.

Dunes: Dunes are intermediate in size, between bars and ripples. Their upstream slope is very shallow and their downstream slope is close to the angle of repose of the bed material. Their height is depth related, typically 10% of the depth. Any surface waves that occur are out of phase with the dunes, that is, minimum water surface elevations occur over the crests of the dunes.

Figure 3.11 Variation of sediment concentration with time



The flow over dunes frequently separates just downstream of the crest, resulting in a re-circulation zone downstream of the dune. The flow reattaches to the upstream face of the next dune downstream. This separation and re-attachment can be important in both the energy dissipation and hence resistance induced by the dune and also can have important implications for the movement of pollutants.

Antidunes: Antidunes usually occur in supercritical flow and form a regular, almost sinusoidal, train of bed forms. Individual antidunes migrate upstream whereas sediment movement is high and in the downstream direction. A train of surface waves occurs in phase with the antidunes. Under certain circumstances these waves break in the upstream direction.

Bars: Bars are major bed forms sometimes covering the full channel width and having lengths, in the direction of flow, usually in excess of the channel width and heights comparable with the mean depth of flow. Point bars are deposits on the inside of channel bends and alternate bars emanate from the left and right bank of the channel in sequence. Alternate bars, or parts of them, have also been referred to as unit bars, linguoid bars, side bars, transverse bars, cross-channel bars and diagonal bars and riffles.

Alternate bars: In otherwise straight reaches of rivers a sequence of bars may form, known as alternate bars. Each bar is attached to the bank, with successive bars attached to opposite banks. As a result, the low flow channel follows a sinuous course from one bank to the other.

Plain bed / transitional bed: When flow conditions are in transition from subcritical to supercritical the bed forms are confused but mainly small in magnitude. The bed may be devoid of bed forms or it may display an array of low-amplitude ripples and dunes or a mixture of all three.

Pool - riffle sequences: The development of alternating areas of deep (pool) and shallow (riffle) flow is characteristic of channels with coarse bed material from approximately a few millimetres upwards. Pools are frequently associated with the outside of bends while on the inside of the bends and extending downstream point bars are often found

Steps and step pool sequences: In steep, particularly small streams the bed is formed by a sequence of steps, often with associated pools, the height of the step being in excess of the normal water depth. The sediments forming the steps are normally too large to be mobilised by the flow. This form of bed feature is common in the headwaters of many upland UK rivers.

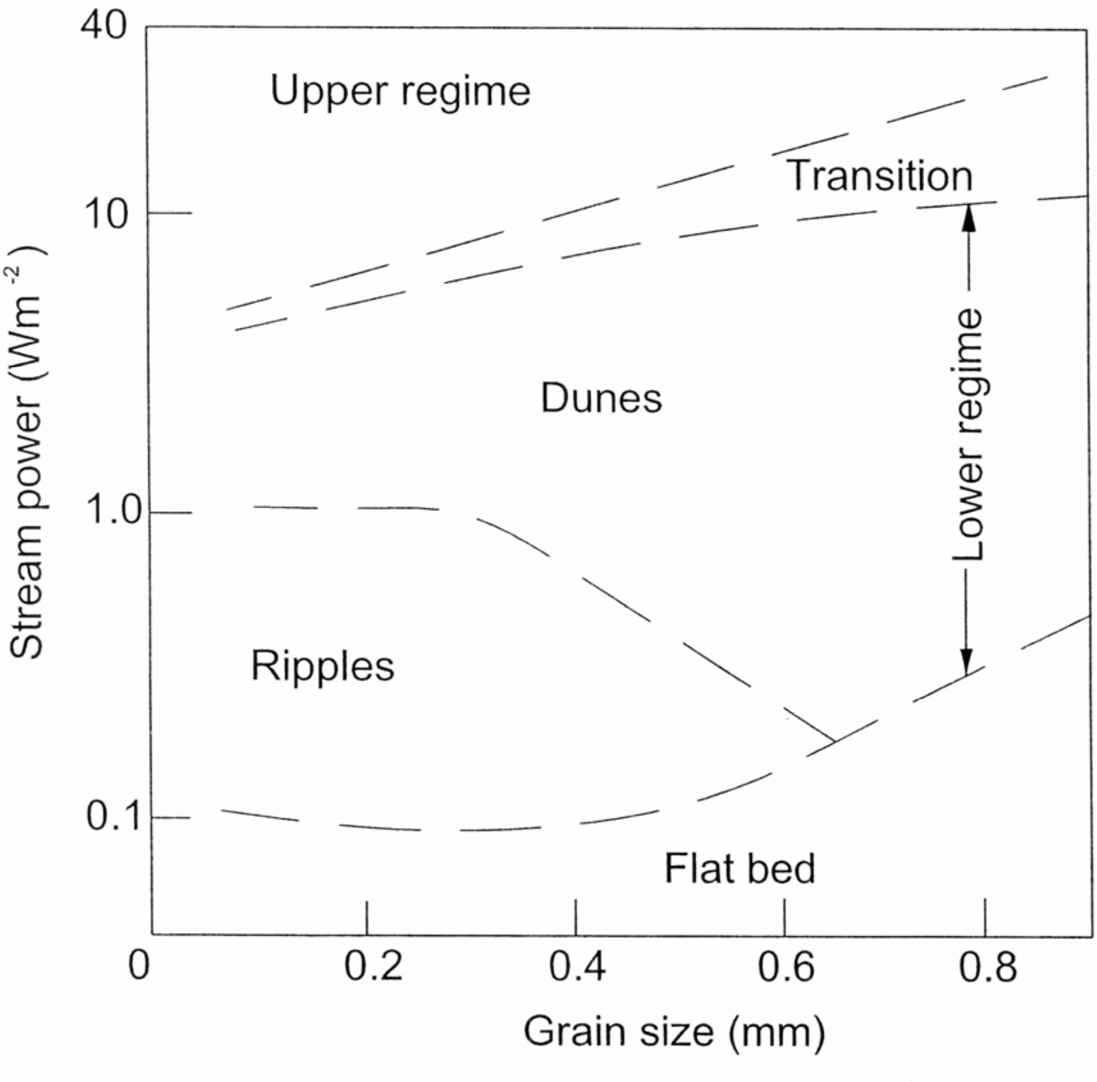
The length scales of ripples are related to the sediment size, the length scales for dunes are related to the flow depth while the length scales for bars is related to the channel width.

Bars (excluding point bars), ripples and dunes all move slowly in the downstream direction. Flow conditions are usually subcritical.

Simons and Richardson (1960) first categorised bed forms as shown in Figure 3.12.

In practice bed features may take a long time to develop and in natural streams, where the flows vary continuously, the bed features are rarely in equilibrium with the instantaneous flow. However, it is useful to interpret the Simons and Richardson categories in terms of the relationship between certain types of bed feature and the corresponding steady flow.

Figure 3.12 Classification of bed features according to Simons et al (1964)



At low flows, where the tractive shear on the bed is less than that required to cause movement of the sediment, there is no correlation between the flow and the bed forms. At flows that are high enough to cause modest sediment transport rates, the bed forms are either ripples or dunes. At higher flows washed out dunes or a plain bed situation occurs. At flows which generate very high sediment transport rates antidunes may occur in sand bed channels. The chutes and pools indicated by Simons and Richardson are mainly restricted to some steep gravel rivers and today would be referred to as pools and riffles.

These bed forms are discussed in greater detail in Section 3.11.

3.9.2 Lower and upper regimes

If the flow is gradually increased in a channel containing fine sand then there is a gradual succession of bed features: plane bed, ripples, dunes, upper plane bed, antidunes and pools and riffles. These are divided as follows into Lower and Upper Regimes with a Transition zone in between:

Lower flow regime	Ripples, dunes with or without ripples superimposed.
Transition:	A range of mainly low amplitude bed features.
Upper flow regime:	Plain bed, antidunes, pools and riffles.

The Lower Regime bed forms are, in general, associated with lower Froude numbers and the Upper Regime with higher Froude numbers. Antidunes are associated with Froude numbers close to 1. It is unlikely, however, that the upper and lower flow regimes can be defined purely in terms of the flow Froude number, without any reference to the nature and size of the bed material. White, Bettess and Wang (1987) presented evidence that suggested that the use of unit stream power to define the transition from the lower flow regime to the upper flow regime was more convincing. Details of using unit stream power to determine whether the flow regime is upper or lower are given in Appendix 3.

3.10 Detailed Description of Bed Features

3.10.1 Ripples

Ripples are small bed forms that are usually less than 0.3m long in the direction of flow and less than 0.03m in height. In longitudinal section, ripples vary from triangular to sinusoidal in shape and their size is not dependent upon flow depth.

Ripples only occur in fine sediments, diameter less than approximately 0.6 mm. Their height is small in comparison with the flow depth and, therefore, there is no associated disturbance of the water surface. Ripples may occur by themselves or they can be found on the backs of dunes. They are first formed at shear stresses only just in excess of that required to move the sediment. Ripples move gradually downstream with a speed that is very much less than the speed of the water.

3.10.2 Dunes

Dunes are intermediate in size, between bars and ripples. Their upstream slope is very shallow and their downstream slope is close to the angle of repose of the bed material. Their height is depth related, typically 10% of the depth. Any surface waves that occur are out of phase with the dunes, that is, minimum water surface elevations occur over the crests of the dunes.

The flow over dunes frequently separates just downstream of the crest, resulting in a re-circulation zone downstream of the dune. The flow reattaches to the upstream face of the next dune downstream. This separation and re-attachment can be important in both the energy dissipation and hence resistance induced by the dune and also can have important implications for the movement of pollutants.

Dunes appear to achieve their maximum height when v_*/ω is approximately 2. For larger sediment this normally means that the maximum height is not achieved. Thus dunes which develop in gravel sediments normally have a small amplitude. As the height of dunes can be up to 10% of the depth of flow they can lead to deformation of the water surface. Dunes move gradually downstream with a speed that is very much less than the speed of the water. The wavelength of dunes appears to be related to the depth of flow by an equation approximately of the form

$$\lambda = 2\pi h,$$

where λ is the wavelength of the dune and
h is the depth of flow
The height of the dune varies with the flow conditions.

Dunes may occur by themselves or they may form at the same time as ripples.

3.10.3 Antidunes

Antidunes occur usually in supercritical flow and form a regular, almost sinusoidal, train of bed forms. Individual antidunes migrate upstream whereas sediment movement is high and in the downstream direction. The formation of antidunes requires the presence of a free water surface and a train of surface waves occurs in phase with the antidunes. Under certain circumstances these waves break in the upstream direction.

Antidunes are normally associated with Froude numbers approaching or exceeding one. As a result antidunes are rarely observed in natural rivers, particularly in the UK.

3.10.4 Bars

Bars are major bed forms, sometimes covering the full channel width and having lengths, in the direction of flow, usually in excess of the channel width and heights comparable with the mean depth of flow. The term ‘bar’ can be used, as in alternate bars, to describe a system that is mobile and progresses downstream, or, as in point bars, to describe stationary features determined by the channel plan form geometry, or to describe transitory features which appear and disappear in braided rivers. Thus unfortunately the term ‘bar’ does not give a precise indication of the nature of the bed feature alluded to.

Point bars are deposits on the inside of channel bends and are thus associated with the plan form of the channel. They are fixed, therefore, in space and do not progress downstream. It should be remembered, however, that the sediment composing such bars is continually changing as sediment is transported downstream and replaced by sediment from upstream.

Mid channel bars form in the middle of channels, frequently associated with bank erosion and channel widening. It is normally difficult to know whether bank erosion and channel widening resulted in lower velocities in the channel and hence bar formation or whether bar formation lead to increased velocities adjacent to the bank and hence bank erosion and channel widening.

Alternate bars emanate from the left and right bank of the channel in sequence. They can occur in otherwise straight reaches of rivers and the bars emanate from the left and right banks in sequence. Each bar is attached to the bank with successive bars attached to opposite banks. As a result the low flow channel follows a sinuous course from one bank to the other. Alternate bars, or parts of them, have also been referred to as unit bars, linguoid bars, side bars, transverse bars, cross-channel bars and diagonal bars and riffles. They normally progress downstream with a velocity that is much lower than that of the flow.

The length of such bed forms is normally several times the channel width and the height can be a significant percentage of the average depth of the channel. Jaeggi (1984) carried out an extensive laboratory investigation on the formation and effects of alternate bars. On the basis of these experiments he formulated conditions for the formation of alternate bars. For further details it is suggested that the original paper is consulted. He also considered the effect that bar formation had on form roughness. The experiments suggested that form roughness is negligible at bar forming flows, which means the flow capacity of a previously plane channel is not altered by the appearance of alternate bars. This also implies that there is no benefit in terms of reduced form losses to be gained by removing alternate bars. Jaeggi did suggest that a number of the standard formulae then in use tended to under-estimate the grain roughness associated with these types of flow.

3.10.5 Plain bed/ transitional

When flow conditions are in transition from subcritical to supercritical the bed forms are confused but mainly small in magnitude. The bed may be devoid of bed forms or it may display an array of low-amplitude ripples and dunes or a mixture of all three.

Experimental evidence would suggest that there is some hysteresis in the transition between upper and lower regime bed forms, that is the transition from lower to upper regime may not take place at the same flow conditions as the transition from upper to lower regime. This adds extra uncertainty in making predictions of hydraulic resistance in this region. Fortunately the transition normally takes place at relatively high Froude numbers, (normally in excess of 0.8) and so is rarely observed in natural rivers, particularly in the UK.

3.10.6 Pool - riffle sequences

The development of alternating areas of deep (pool) and shallow (riffle) flow is characteristic of channels with coarse bed material from approximately a few millimetres upwards. Pools are frequently associated with the outside of bends while on the inside of the bends and extending downstream point bars are often found. These bed features give an asymmetric shape to the cross-sections, even in otherwise straight, uniform reaches. It is common to have gravel bars, forming the riffles, alternating with the pools. The shape of the bars is often such that the lowest part of the bed (thalweg) follows a sinuous course down the river.

It is found on many rivers that the pool – riffle spacing is more or less regular and is correlated with the channel width. It should be remembered that both the pool- riffle spacing and the channel width are subject to significant spatial variations and any relationship is not precise. Keller and Melhorn (1978) reported pool to pool spacing ranging from 1.5 to 23.3 times the channel width but more commonly it is found that the pool – riffle spacing is about 5 to 7 channel widths. Similar spatial changes in bed level have even been observed in streams on glaciers where no sediment is present (Knighton, 1981) and so the phenomena does not seem to be specifically related to sediment.

The bed surface sediments on the riffles are normally coarser than the bed surface sediments in the pools. Hey and Thorne found that in a particular reach the D_{50} size of the riffle material was approximately 20% larger than the average D_{50} size for all the river sediments.

At low and medium flows the riffles act to retain water in the pool upstream. The flow in the pool is normally relatively deep and slow while the flow over the riffle is relatively shallow and fast. During low flow periods pools tend to trap fine sediments while the flow over the riffles acts to clear silt from voids between the coarser sediment on the riffle. This is important to ensure the oxygenation of fish eggs laid in redds in the riffle, see Chapter 10. The pools also act as refuges for fish, see Chapter 10.

It has also been found the bankfull channel width at riffles is slightly wider than for the rest of the channel thus at riffles the channel tends to be wider and shallower than elsewhere (Hey and Thorne, 1986).

The impact of pool – riffle sequences on the flow tends to reduce as the discharge increases until at very high flows, when the depth is large in comparison with the depth variation between pool and riffle, they just act as large bed features. Thus at high flows the differences between pools and riffles reduces. It has been suggested that at high flows the shear stress in the pools may exceed that on the riffles, though it is difficult to imagine situations where this might occur.

Pool – riffle sequences appear to be remarkably stable and in some circumstances may persist for periods in excess of a hundred years. Large floods can destroy such sequences but this appears to be the exception rather than the rule. In general, providing suitable mobile sediment is available on the bed of a river, the formation of pool – riffle sequences will occur naturally.

For river restoration the natural development of pool – riffle sequences is very helpful. Though it is better to start with some approximation to an equilibrium form, it is normally found that, providing suitable bed material is available, the flow in a river channel will rapidly develop its own natural pool – riffle sequences.

There is, at the moment, no wholly satisfactory explanation for the formation of pool and riffles.

3.10.7 Steps and step-pools

In steep, particularly small streams, the bed is formed by a sequence of steps, often with associated pools, the height of the step being in excess of the normal water depth. The sediments forming the steps are normally too large to be mobilised by the flow. This form of bed feature is common in the headwaters of many upland UK rivers.

The hydraulic resistance of such streams is large and difficult to assess. In many cases the height of the 'roughness elements' exceeds the depth of flow which violates the assumptions underlying many of the equations such as Colebrook-White.

3.10.8 Prediction of the nature of bed features

The section above gives a detailed description of the different forms of bed features that might occur but it gives no indication of how to determine what type of bed features will develop under particular circumstances. As has been hinted at above the physical processes responsible for the development of different bed features are different and also not fully understood. This makes the determination of the bed form character under particular flows difficult. A number of authors have selected what they consider to be meaningful physical parameters and then plotted data for different bed forms on these plots. They have then tried to identify areas corresponding to different bed features, for example, Simons et al (1964), see Figure 3.12; Hill (1967), see Figure 3.13 and van Rijn (1984), see Figure 3.14. The interpretation of such figures is always fraught with difficulty. The data usually comes almost exclusively from laboratory experiments. The categorisation of the bed features by the original experimenters may not always be consistent and the delineation of the areas corresponding to different bed features may be a function of the absence or presence of data. The addition of more data from a wider range of flow conditions, sediment sizes or sediment transport rates may lead to a more confused picture rather than leading to greater delineation and clarity. With these reservations in mind the Figures 3.12 to 3.14 can normally be used to obtain a qualitative picture of the type of bed feature that may be present under particular flows.

Figure 3.13 Classification of bed features according to Hill et al (1967)

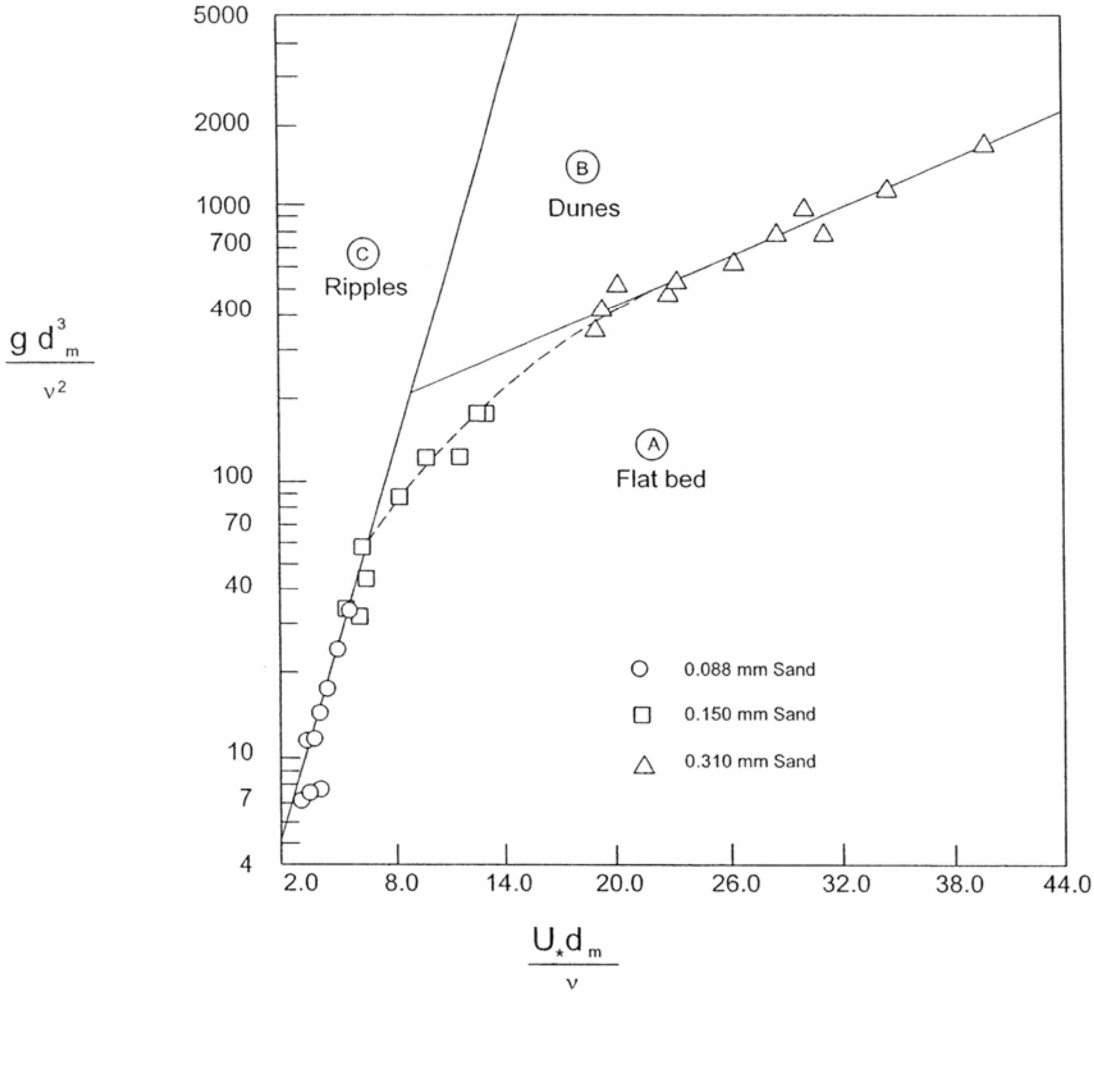
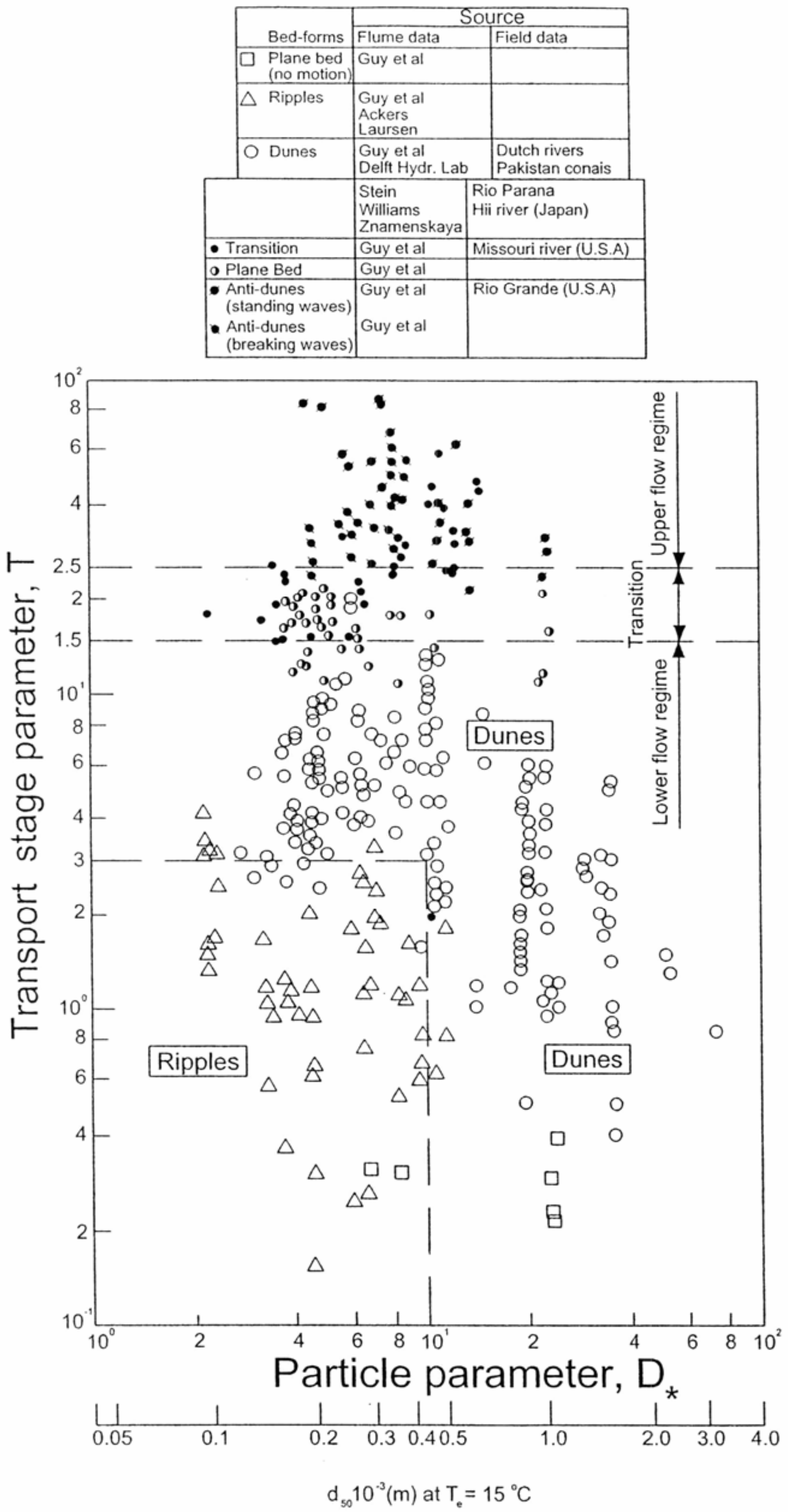


Figure 3.14 Classification of bed features in terms of transport parameter T and dimensionless particle size D*, according to van Rijn (1984)



3.11 Grain and Form Roughness

In determining the overall alluvial resistance it is important to distinguish between the roughness associated with the sediment grains (grain roughness) and the roughness associated with bed forms (form roughness). In some circumstances grain roughness predominates eg in pipes, artificial channels and gravel rivers not subject to pool and riffle formations. In other situations form roughness predominates, for example, in rivers with sand beds. In many cases both types of roughness are significant and a grain sized roughness surface is superimposed upon the bed features.

Grain roughness: This is the roughness associated with the sediment grains. The usual measure is the D_{90} size of the bed sediments and the Colebrook-White effective roughness height is approximately 3 times D_{90}. The grain roughness in gravel rivers is normally large as a result of the size of the bed material, while bed features are normally low. The result is that the form roughness for gravel beds is normally smaller than the grain roughness and so the roughness is dominated by the grain roughness.

Form roughness: The roughness associated with the expansion and contraction of the flow as it passes over the bed forms. Bed forms vary in size dependent upon the nature of the sediment and the ambient flow conditions and hence the magnitude of the form roughness also varies.

Overall alluvial resistance comprises a combination of grain and form resistance with form resistance predominating in most practical situations. Researchers have frequently taken a direct approach and have developed means of relating roughness coefficients directly to the nature of the bed sediments and the ambient flow conditions. These methods are described in Chapter 7.

3.12 Bed Form Characteristics

3.12.1 Geometric data

Attempts have been made to relate the amplitude and wavelength of bed features, particularly dunes, to the prevailing flow conditions (van Rijn, 1984 and Karim, 1995). See Appendix 4 for a description of these theories.

In an approach such as van Rijn's, one assumes that the size and shape of the dune is deterministic, that is, it is a unique function of the flow conditions. An alternative approach is a stochastic one, as is used, for example, for wind-generated water waves. In this approach one assumes that a number of wavelengths will be present but that the overall shape of the wave spectra will be governed by the imposed conditions. In the case of water waves this is the wind speed and fetch whereas for bed features it is the flow conditions and sediment size. Nordin (1971) presented examples of spectra produced for a number of cases. This type of approach is attractive and may have great potential for interpreting laboratory data. In natural rivers this approach has limitations due to the temporal and spatial variability. Changes in flow mean that the bed features rarely relate entirely to the flow at the moment but depend in part upon the previous flow history and spatial variability mean that the flow conditions are rarely uniform for more than a few metres.

3.12.2 Surface roughness of gravel beds

The surface roughness of sediment beds is frequently expressed in terms of a roughness length or k_s value. For sand sizes this is based on a comparison with experiments carried out by Nikuradse in which he roughened surfaces by gluing uniformly-graded sand to a pipe surface. The roughness of other surfaces can then be expressed as the size of sand that, as a uniform coating, would give the same resistance under rough turbulent flow. Such k_s values are available for a range of materials, see HR Tables for the design of pipes and sewers).

It is implicit in this approach that the only relevant parameter is the size of the sand grains and that their orientation is unimportant. This is a reasonable assumption for fine sediments but for coarse sediments it would appear that both size and orientation are important.

The Universities of Aberdeen and Glasgow have carried out degradation experiments in which a bed is degraded until equilibrium occurs. Initially sediment transport takes place but then gradually it reduces until there is no effective transport. It was found that after sediment transport had ceased, the roughness of the bed continued to change, gradually increasing with time. This was despite the fact that the composition of the surface material was no longer changing. It would appear that a process of particle re-orientation was taking place which led to the increase in roughness. At the end of the experiment there was evidence of a coherent structure to the particles on the bed. Thus it would appear that, though for gravel beds the sediment size is a dominant factor in the roughness of the surface, it can also be influenced by particle orientation and flow history.

3.13 Development of Bed Features

When bed forms develop from a plane bed there is normally no change in average bed level. Thus the volume of sediment above the average bed level in the crests of the features is compensated by the volume of the troughs below the average bed level. This has implications for the speed of development of bed features. For bed features such as dunes and ripples to develop then all that is needed is for the appropriate volume of sediment within the bed feature to be re-arranged on the bed. This volume is normally quite small in comparison with the total volume of sediment transport and so changes in the size of bed features occurs rapidly, for example, during a flood event. The re-arrangement of sediment on the bed still takes some time and so if the flow is changing rapidly then it may be that the equilibrium bed form is never achieved.

In a laboratory the time to go from a flat bed to the fully developed dune height can be of the order of 1 hour while the development of dune length takes of the order of 2 hours (Wijbenga and Klaasen, 1981 and Klaasen et al, 1986). van Urk (1982) reported that on the lower Rhine the time lag between flow and dune height was 4 days, with a longer period for dune length.

This rapid development of ripples and dunes has implications for channel maintenance. If ripples or dunes are removed by flattening of the bed then it is likely that the change will be extremely temporary. During the next flood event the bed features will reform on a time scale shorter than the duration of the flood.

Large bed features such as bars contain relatively larger volumes of sediment and thus take relatively longer to form. They are still likely to form over only one or two flood events.

3.14 Speed of Movement of Bed Forms

Some bed features are stable, for example, point bars on the inside of meander bends. These may grow or reduce in size dependent upon the flow but either they do not move or they migrate with the meander bend at a slow speed determined by the movement of the bend. Other bed features migrate either downstream, as in the case of dunes and ripples, or upstream, as in the case of anti-dunes. A number of empirical formulae have been suggested to predict the speed of movement of dunes and ripples.

Speed of movement of dunes

Snamenskaya (1969) derived a plot involving the dune wave speed. On a figure of Froude number against V/ω he plotted contours of dune steepness and speed.

Orgis (1974) derived an expression from laboratory data for the speed of a dune in the form

$$\frac{cd}{w} = Ad^{2/3}\frac{Fr^3}{1-Fr^2} \tag{3.1}$$

where A= 0.4×10^6 for minimum speed,
1.7×10^6 for mean speed and
5.1×10^6 for maximum speed.

It is to be noted that the Orgis equation does not depend upon sediment size, which suggests that it is unlikely to be applicable to a full range of sediment sizes.

Such expressions for the speed of movement of dunes should be regarded as only giving a very approximate indication of dune speed.

In laboratory experiments dune wave speeds have been measured in the range of 0.3 to 70 mm/minute. These were for lower regime bed forms. The speed of antidunes can be an order of magnitude larger. It is likely that in natural rivers the range of wave speeds is larger.

The speed of movement and size of dunes are intimately connected with the sediment transport rate. One of the ways of measuring bed load is to measure the speed of migration of bed features which, together with the volume of the dunes, provides an estimate of the amount of sediment transport. There is thus a relationship between theories of bed load, size of bed features and speed of movement of bed features.

4 Data Collection and Analysis

4.1 Introduction

A general understanding of alluvial river systems and the specific and quantitative determination of sediment processes and alluvial resistance in alluvial water courses involves (1) the collection of field data, (2) the analysis of these data and (3) the use of predictive techniques to deduce sediment processes. Chapters 6 and 8 deal with predictive techniques for sediment transport and alluvial resistance, respectively. This chapter concerns the acquisition and interpretation of data.

4.2 Study Requirements

A particular study may require any of the following data:

Catchment characteristics
1. Topographic maps (scale and contour interval are important)
2. Aerial photographs (scale and accuracy are important)
3. Remote sensing (vegetation, urban areas, etc)
4. Rock, soil and sediment data (sizes, formations, erodibility, etc)
5. Morphological information on historic river channels (location, size, slope, etc)

Erosion characteristics
1. Geological mapping (outcrops, exposed bedding, etc)
2. Soil surveys (size, cohesiveness, etc)
3. Stability of river banks (size and cohesiveness of sediments, vegetation, etc)

Hydrological
1. Rainfall (average annual, short term intensity, seasonal distribution, etc)
2. Runoff (flood flows, daily means, annual means, annual distribution, etc)
3. Wind data for soil erosion (direction, intensity, duration, etc)

Hydraulic
1. Channel cross-sections
2. Channel slope
3. Roughness characteristics of channel
4. Calibration data in the form of observed discharges and corresponding water levels

Sediment erosion, transport and deposition
1. Bed material samples (size(s), shape, spatial distribution, etc)
2. Bed load samples (particles being transported close to the bed)
3. Suspended load samples (particles travelling in suspension)
4. Reservoir surveys (sediment deposition, delta formation, downstream degradation and armouring)
5. General distribution of sediments (bends, confluences, deltaic areas, etc)

For the purposes of this manual it is assumed that the data associated with the first three categories above are generally available, either in the literature or from previous studies in the geographical area. Data collection for the detailed sediment aspects in the final category above is the subject of the Section 4.4.
There is increasing concern about issues which are sediment related such as:

- the impact of land-use change within a catchment,
- the impact of global warming,
- movement of pollutants within river systems,
- changes in ecology and fisheries within a river system.

At present there is no systematic, routine sediment data collection in the UK that will provide information on the sediment aspects of such problems. The only studies that have been carried out in the past are site-specific and short-term. Without systematic long-term sediment records it will be difficult to resolve or assess many of the changes that are taking place in UK rivers.

4.3 Preliminary Investigations

4.3.1 Review of existing data

Any existing data relating to the area should be collected and critically examined.

4.3.2 Site Reconnaissance

A site inspection is important at the outset in order to gain a first hand knowledge of the catchment, the river system and also details of the nature of the sediments and their spatial distribution. The inspection should be on the ground and it is useful to take photographs of salient features – include a scale in the photograph if size is relevant. For remote and extensive catchments it may be of value to include an inspection by aeroplane or helicopter in which case aerial photographs should be taken.

In assessing an existing river system and the potential impact of proposed engineering works, it is important to identify characteristic forms and features of the river and the fluvial processes responsible for generating and maintaining them. This is frequently the role of the geomorphologist. In the absence of quantitative relationships, much of this work is qualitative in nature.

Fieldwork is normally essential to obtain a full understanding of a particular river reach. To aid in recording and assessment in the field various authors have attempted to produce guidelines to carrying out such field work, see for example (Thorne 1998). Such guidelines help in:

a) ensuring all relevant information is collected during a site visit,
b) data is recorded in a systematic way,
c) providing some indication of possible interpretations.

Figures 4.1 and 4.2 reproduce just two pages of a seven page Streem Reconnaissance Record Sheet developed by Professor Thorne. They are taken from Thorne C. R., 1998, Stream Reconnaissance Handbook, copyright John Wiley and Sons Ltd and are here reproduced with permission.

Figure 4.1 Extract from Thorne's stream reconnaissance sheet

STREAM RECONNAISSANCE RECORD SHEET

Developed by Colin R. Thorne
Department of Geography, University of Nottingham, NG7 2RD, UK

SECTION 1 – SCOPE AND PURPOSE

Brief Problem Statement:-

Purpose of Stream Reconnaissance:-

Logistics of Reconnaissance Trip:-

RIVER LOCATION DATE

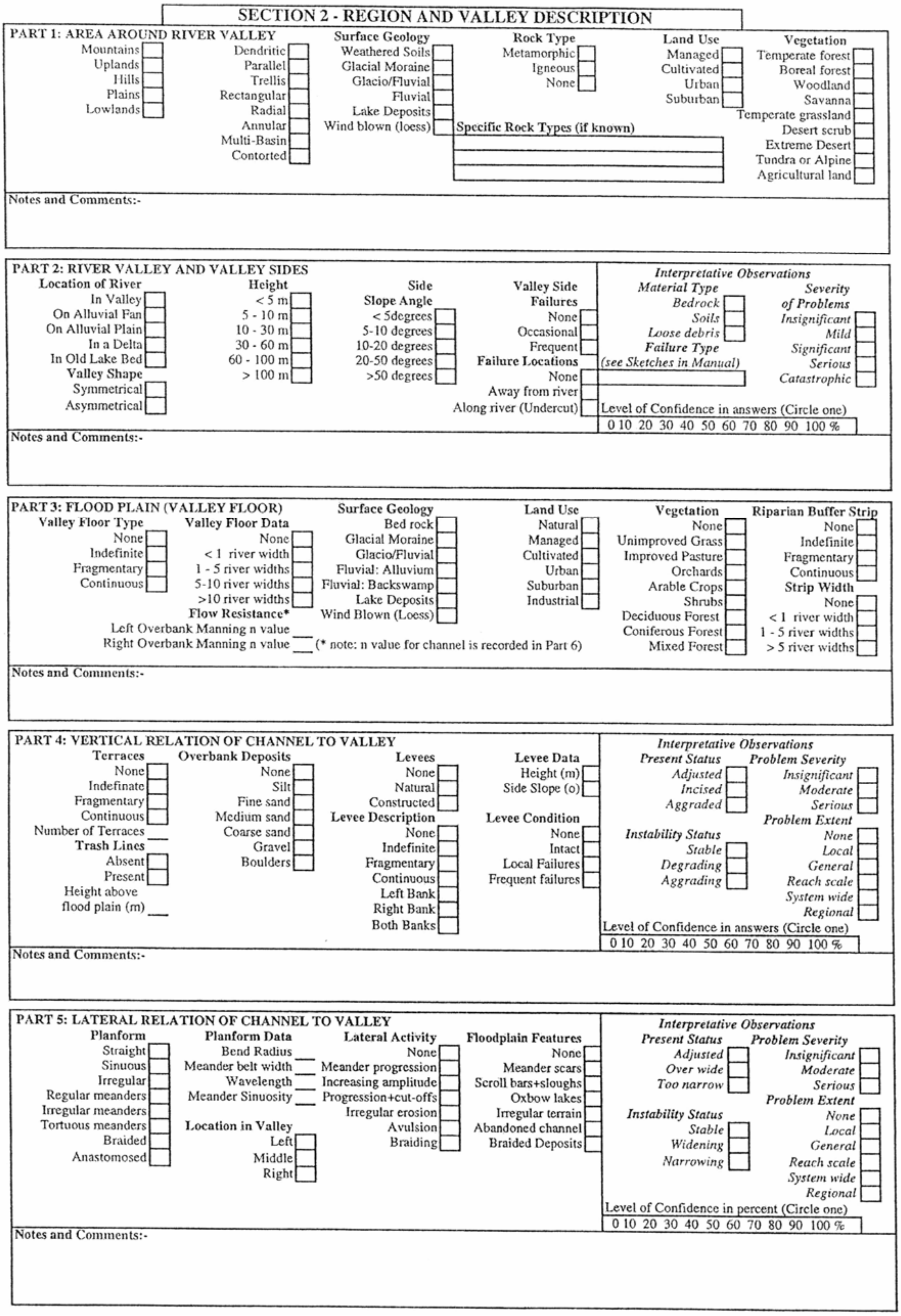
PROJECT STUDY REACH From To

SHEET COMPLETED BY

RIVER STAGE TIME: START TIME: FINISH

General Notes and Comments on Reconnaissance Trip:-

Figure 4.2 Further extract from Thorne's stream reconnaissance sheet



SECTION 2 - REGION AND VALLEY DESCRIPTION

PART 1: AREA AROUND RIVER VALLEY

Mountains ☐ Uplands ☐ Hills ☐ Plains ☐ Lowlands ☐

Dendritic ☐ Parallel ☐ Trellis ☐ Rectangular ☐ Radial ☐ Annular ☐ Multi-Basin ☐ Contorted ☐

Surface Geology: Weathered Soils ☐ Glacial Moraine ☐ Glacio/Fluvial ☐ Fluvial ☐ Lake Deposits ☐ Wind blown (loess) ☐

Rock Type: Metamorphic ☐ Igneous ☐ None ☐

Specific Rock Types (if known) ____

Land Use: Managed ☐ Cultivated ☐ Urban ☐ Suburban ☐

Vegetation: Temperate forest ☐ Boreal forest ☐ Woodland ☐ Savanna ☐ Temperate grassland ☐ Desert scrub ☐ Extreme Desert ☐ Tundra or Alpine ☐ Agricultural land ☐

Notes and Comments:-

PART 2: RIVER VALLEY AND VALLEY SIDES

Location of River: In Valley ☐ On Alluvial Fan ☐ On Alluvial Plain ☐ In a Delta ☐ In Old Lake Bed ☐

Valley Shape: Symmetrical ☐ Asymmetrical ☐

Height: < 5 m ☐ 5 - 10 m ☐ 10 - 30 m ☐ 30 - 60 m ☐ 60 - 100 m ☐ > 100 m ☐

Side Slope Angle: < 5degrees ☐ 5-10 degrees ☐ 10-20 degrees ☐ 20-50 degrees ☐ >50 degrees ☐

Valley Side Failures: None ☐ Occasional ☐ Frequent ☐

Failure Locations: None ☐ Away from river ☐ Along river (Undercut) ☐

Interpretative Observations

Material Type: *Bedrock* ☐ *Soils* ☐ *Loose debris* ☐

Failure Type *(see Sketches in Manual)* ____

Severity of Problems: *Insignificant* ☐ *Mild* ☐ *Significant* ☐ *Serious* ☐ *Catastrophic* ☐

Level of Confidence in answers (Circle one)
0 10 20 30 40 50 60 70 80 90 100 %

Notes and Comments:-

PART 3: FLOOD PLAIN (VALLEY FLOOR)

Valley Floor Type: None ☐ Indefinite ☐ Fragmentary ☐ Continuous ☐

Valley Floor Data: None ☐ < 1 river width ☐ 1 - 5 river widths ☐ 5-10 river widths ☐ >10 river widths ☐

Flow Resistance*
Left Overbank Manning n value ___
Right Overbank Manning n value ___ (* note: n value for channel is recorded in Part 6)

Surface Geology: Bed rock ☐ Glacial Moraine ☐ Glacio/Fluvial ☐ Fluvial: Alluvium ☐ Fluvial: Backswamp ☐ Lake Deposits ☐ Wind Blown (Loess) ☐

Land Use: Natural ☐ Managed ☐ Cultivated ☐ Urban ☐ Suburban ☐ Industrial ☐

Vegetation: None ☐ Unimproved Grass ☐ Improved Pasture ☐ Orchards ☐ Arable Crops ☐ Shrubs ☐ Deciduous Forest ☐ Coniferous Forest ☐ Mixed Forest ☐

Riparian Buffer Strip: None ☐ Indefinite ☐ Fragmentary ☐ Continuous ☐

Strip Width: None ☐ < 1 river width ☐ 1 - 5 river widths ☐ > 5 river widths ☐

Notes and Comments:-

PART 4: VERTICAL RELATION OF CHANNEL TO VALLEY

Terraces: None ☐ Indefinate ☐ Fragmentary ☐ Continuous ☐
Number of Terraces ___

Trash Lines: Absent ☐ Present ☐
Height above flood plain (m) ___

Overbank Deposits: None ☐ Silt ☐ Fine sand ☐ Medium sand ☐ Coarse sand ☐ Gravel ☐ Boulders ☐

Levees: None ☐ Natural ☐ Constructed ☐

Levee Description: None ☐ Indefinite ☐ Fragmentary ☐ Continuous ☐ Left Bank ☐ Right Bank ☐ Both Banks ☐

Levee Data: Height (m) ☐ Side Slope (o) ☐

Levee Condition: None ☐ Intact ☐ Local Failures ☐ Frequent failures ☐

Interpretative Observations

Present Status: *Adjusted* ☐ *Incised* ☐ *Aggraded* ☐

Instability Status: *Stable* ☐ *Degrading* ☐ *Aggrading* ☐

Problem Severity: *Insignificant* ☐ *Moderate* ☐ *Serious* ☐

Problem Extent: *None* ☐ *Local* ☐ *General* ☐ *Reach scale* ☐ *System wide* ☐ *Regional* ☐

Level of Confidence in answers (Circle one)
0 10 20 30 40 50 60 70 80 90 100 %

Notes and Comments:-

PART 5: LATERAL RELATION OF CHANNEL TO VALLEY

Planform: Straight ☐ Sinuous ☐ Irregular ☐ Regular meanders ☐ Irregular meanders ☐ Tortuous meanders ☐ Braided ☐ Anastomosed ☐

Planform Data: Bend Radius ___ Meander belt width ___ Wavelength ___ Meander Sinuosity ___

Location in Valley: Left ☐ Middle ☐ Right ☐

Lateral Activity: None ☐ Meander progression ☐ Increasing amplitude ☐ Progression+cut-offs ☐ Irregular erosion ☐ Avulsion ☐ Braiding ☐

Floodplain Features: None ☐ Meander scars ☐ Scroll bars+sloughs ☐ Oxbow lakes ☐ Irregular terrain ☐ Abandoned channel ☐ Braided Deposits ☐

Interpretative Observations

Present Status: *Adjusted* ☐ *Over wide* ☐ *Too narrow* ☐

Instability Status: *Stable* ☐ *Widening* ☐ *Narrowing* ☐

Problem Severity: *Insignificant* ☐ *Moderate* ☐ *Serious* ☐

Problem Extent: *None* ☐ *Local* ☐ *General* ☐ *Reach scale* ☐ *System wide* ☐ *Regional* ☐

Level of Confidence in percent (Circle one)
0 10 20 30 40 50 60 70 80 90 100 %

Notes and Comments:-

4.3.3 Aerial photography and remote sensing

At an early stage of an investigation remote sensing can provide much general information about the project area. This technology has made enormous strides in the last 30 years and the resolution achieved has improved continuously. Satellite images now have a ground resolution better than 10 m and low level aerial photography can yield ground resolutions better than 1 m. There is also a variety of types of image which can detect ground temperatures, vegetation, etc, as well as the more obvious visible features of rivers, mountains, urban infrastructure.

4.4 Acquisition of Data

The acquisition of field data is a time consuming and often expensive exercise. It is important, therefore, that the programme of data acquisition only covers those aspects which are necessary to fulfil the objectives of the study to hand. However, the range of measurements required for a particular study is often extensive. River behaviour and sediment transport rates depend upon many factors including hydrological and geological aspects. Fortunately, much of the general data will often be available from other sources and the detailed measurements for a specific project will be spared the expense associated with the more general data collection. The data which is collected for a particular study should be well documented and summarised in a form which can easily be understood by subsequent users of the data.

4.4.1 Sediment in rivers

Sampling bed material
A knowledge of the nature of bed sediments is fundamental to the prediction of sediment processes. In some circumstances the bed sediments are easily described, in others the sediments are formed of complex mixtures of different sized particles and are less easy to describe.

Bed sediments in lowland rivers mainly comprise fine sands and silts whereas bed sediments in mountain rivers frequently comprise mainly coarse sands, gravels and boulders. Low gradient rivers exhibit bed sediments of a near uniform size whereas the range of sizes found in the bed material in steep rivers is large. Particle shape also varies with sediment size. Large bed material can be flat and elongated reflecting the structure of the parent rocks from which it is derived. Fine material, which has undergone much fracturing and abrasion, tends to be more spherical in shape.

Sand bed rivers:

In many sand bed channels the bed is permanently under water and hence it is aften necessary to obtain samples of bed material under running water although occasionally there will be exposed shoals which are representative of the bed material generally. To obtain satisfactory samples of the bed material from under flowing water, the sampler should enclose a volume of the sediment and then protect the sample from the currents while it is being brought to the surface.

Samplers for obtaining material moderately close to the surface of the bed include the following types:-

1. Hand held bed surface samplers (sampling cylinders, pipe scoops, bag scoops)
2. Hand held core samplers (push or hammer corers, freeze-core samplers)
3. Remotely operated lightweight bed surface samplers (pipe scoops, bag scoops, drag buckets, grab samplers)
4. Remotely operated lightweight core samplers (push or hammer corers)
5. Remotely operated heavyweight bed surface samplers (anchor dredges, grab samplers)
6. Remotely operated heavyweight core samplers (free fall gravity corers, frame guided gravity corers, vibro-corers)

Drag and grab bucket samplers normally suffer some loss of material whilst transiting the water column. Core samplers suffer less in this respect.

When sampling to obtain data on the vertical composition of the bed material deposits, deep undisturbed samples are needed. This is usually obtained using free fall gravity corers, frame guided gravity corers or vibro-corers

Further details are available in Petersen (1986) and British Standards Institution (1996). Examples of bed material samplers are shown in Figure 4.3.

Gravel rivers:

The samplers described for sand bed rivers are not appropriate for gravel rivers where much larger samples are required and where there is no practical way of sampling under water. Gravels, cobbles and boulders are extremely difficult to sample because penetration of the surface is difficult and also there is a requirement to collect large amounts of material in order to gain a representative sample which makes collection and transport of samples cumbersome. Manual collection is recommended and the stream must either be dry or there must be exposed shoals of material which are representative of the bed material as a whole.

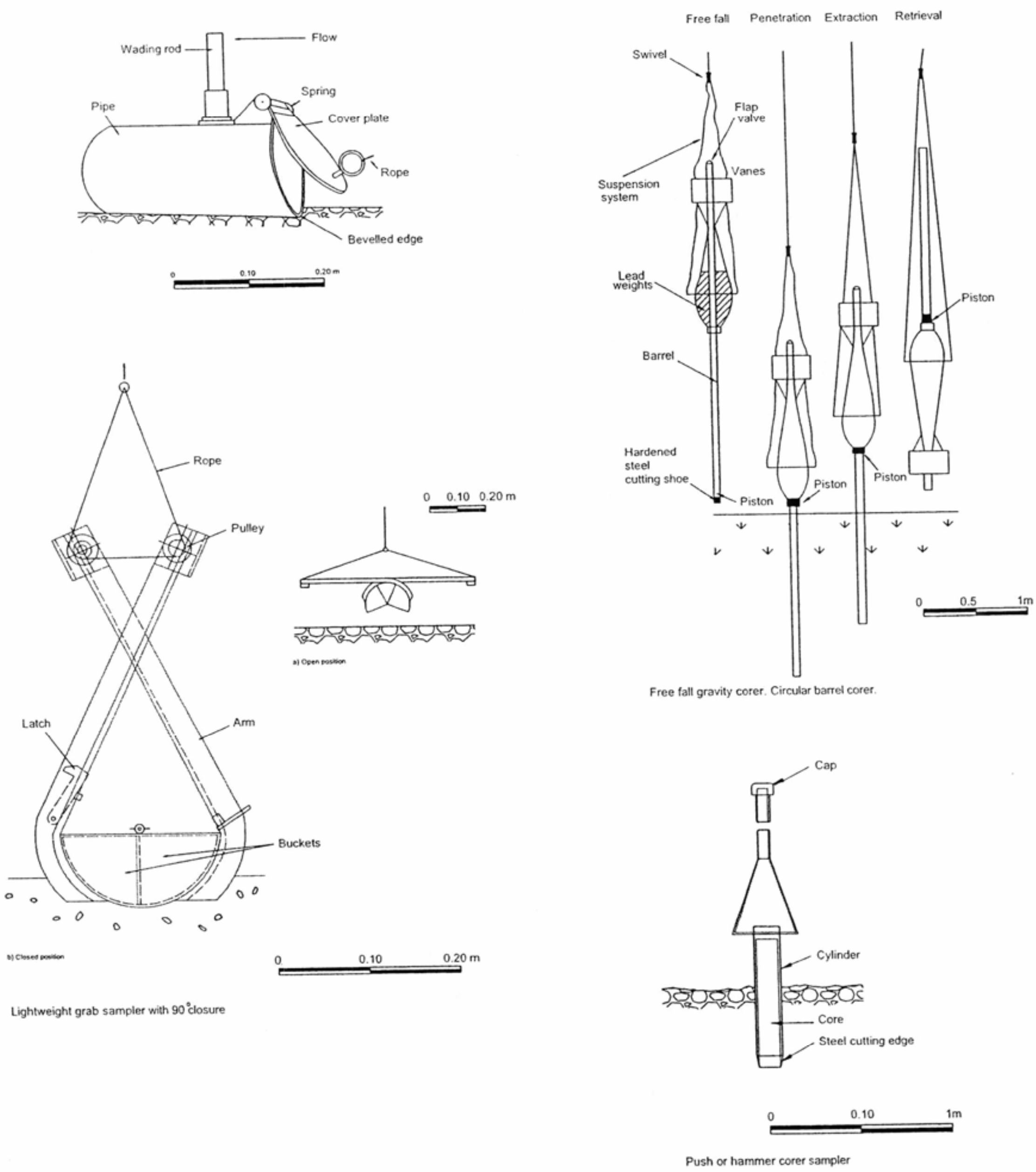
Two methods are recommended for obtaining surface samples:-

1. The grid method
2. The linear or Wolman method

In the first method a frame is made up and a rectangular grid of wires is stretched across the frame at regular intervals. The size of the frame and the spacing of the wires depends on the size of the bed material to be sampled. If the maximum size of the sediment visible on the surface is less than 100 mm then a frame 1.5 m x 1.5 m will be appropriate with wire spaced at 100 mm intervals. Otherwise a frame 2.25 m x 2.25 m is preferred with a wire spacing of 150 mm. The frame is positioned over a representative area of the bed and the particle beneath each intersection is extracted. The 200 or so particles so obtained represent the surface bed material.

The second method removes the need for the measurement frame. The observer chooses a suitable large area of exposed bed sediment and strides across it picking up the nearest particle in front of his feet at each stride. This method samples a wider area but can be subjective in that the observer may be selective in where he chooses to tread. Again, about 200 particles are required for a representative sample.

Figure 4.3 Types of bed material sampler



Note that due to the sampling method, the same sediment bed sampled by these two methods would produce samples with different characteristics. Allowance for this can be made when analysing the samples, see BS 3680/ISO9195.

The two methods described above essentially measure the surface texture of a gravel bed. This is not representative of an in depth sample even if the composition of the bed material is uniform with depth. Kellerhals and Bray (1971) have shown how to convert the observed surface sample to the equivalent volume sample, assuming the composition of the bed material is invariant with depth.

In many gravel rivers the surface will be armoured. This can be checked by removing the surface layer of bed material and exposing the sub-layer(s). If the bed is armoured, particle sizes in the sub-layer will be much smaller than the particle sizes in the surface layer. Under these circumstances obtaining a surface sample is insufficient to define the bed material adequately. A volume sample is required. This can be obtained, with difficulty and some inaccuracy, using a pipe sampler or a gravel cutter sampler but the most reliable way is to obtain an in situ sample of the bulk material by excavating a rectangular pit and carefully collecting the excavated material for subsequent size analysis. For information on sampling methods and sample sizes see BS 3680/ISO 9195 and ISO 4364

Recently image analysis has been used to determine the size composition of bed samples. This method is still under development but it holds out the prospect of rapid determination of surface composition. The method should have the ability to sample gravel beds at a large number of locations, which would help in the characterisation of the variation in gravel composition on the bed of a river channel. The technique also has potential for use in both the field and the laboratory (McEwan et al, 2000).

Sampling the bed load

Bed load transport varies both with time and location in the stream bed. Movement of bed load particles changes the shape and location of bed features, such as ripples, dunes and bars, which in turn changes flow patterns and bed load transport rates. The inference from this is that a single measurement of bed load transport at a particular location on the stream bed is of very little value in understanding general bed load transport.

To measure overall bed load transport in a stream using sampling techniques requires repetitive measurements at several locations across the width of the channel. Bed features move slowly downstream which means that measurements must either be carried out over an extended period at a particular location or undertaken at several cross-sections in the streamwise direction.

Bed load transport rates are usually measured using samplers, but other less well known techniques are also applied. These include:-

- measurements of the migration of bed forms
- measurements of the migration of tracer particles in the streamwise direction
- measurements of net erosion and deposition in a defined reach
- measurements of the number, size and velocity of bed load particles
- measurements using purpose built sediment traps covering part or all of the channel width

These latter methods tend to yield time averaged results whereas samplers provide short term localised bed load transport rates.

Bed load samplers inevitably affect flow patterns in their close proximity. This means that they do not catch undisturbed “true” samples of the sediment approaching the sampler from upstream. There are many different sampler designs and in many cases the developers of particular samplers have tested their so called “efficiency” by comparing sediment collected by the sampler with sediment collected using an alternative method such as a relatively large sediment trap. Most of this work has been done in laboratory conditions with relatively small sediment sizes and it has been implicitly assumed that the alternative method is error-free. This is clearly not true. It has been suggested that efficiencies vary with the size distribution of the sediment, the flow conditions, the rate of bed load transport and the degree of filling of the sampler.

A technical report on the measurement of bed load transport is produced by the International Standards Organisation (1992a). It is significant that this is a Technical Report, not a Standard. The science has not developed to the point where specific devices for sampling bed load transport can be recommended with confidence. The measurement of bed load transport rates remains difficult and inaccurate. Examples of bed load samplers are shown in Figure 4.4.

Sampling the suspended sediment load

The suspended load comprises the wash load (fine materials travelling entirely in suspension) and the suspended bed material load (coarser materials which form part of the total bed material load). Measurements of the suspended load therefore include fine, usually cohesive, particles as well as coarser, non-cohesive, materials.

For the purpose of understanding river behaviour and also the consequences of imposed changes to rivers, it is necessary to deduce the total bed material load because this is the dominating influence on river processes. Thus the measured suspended load must, at the analysis stage, be divided into coarse materials (the suspended bed material load) and fine materials (the wash load). The addition of the suspended bed material load to the bed load gives the total bed material load.

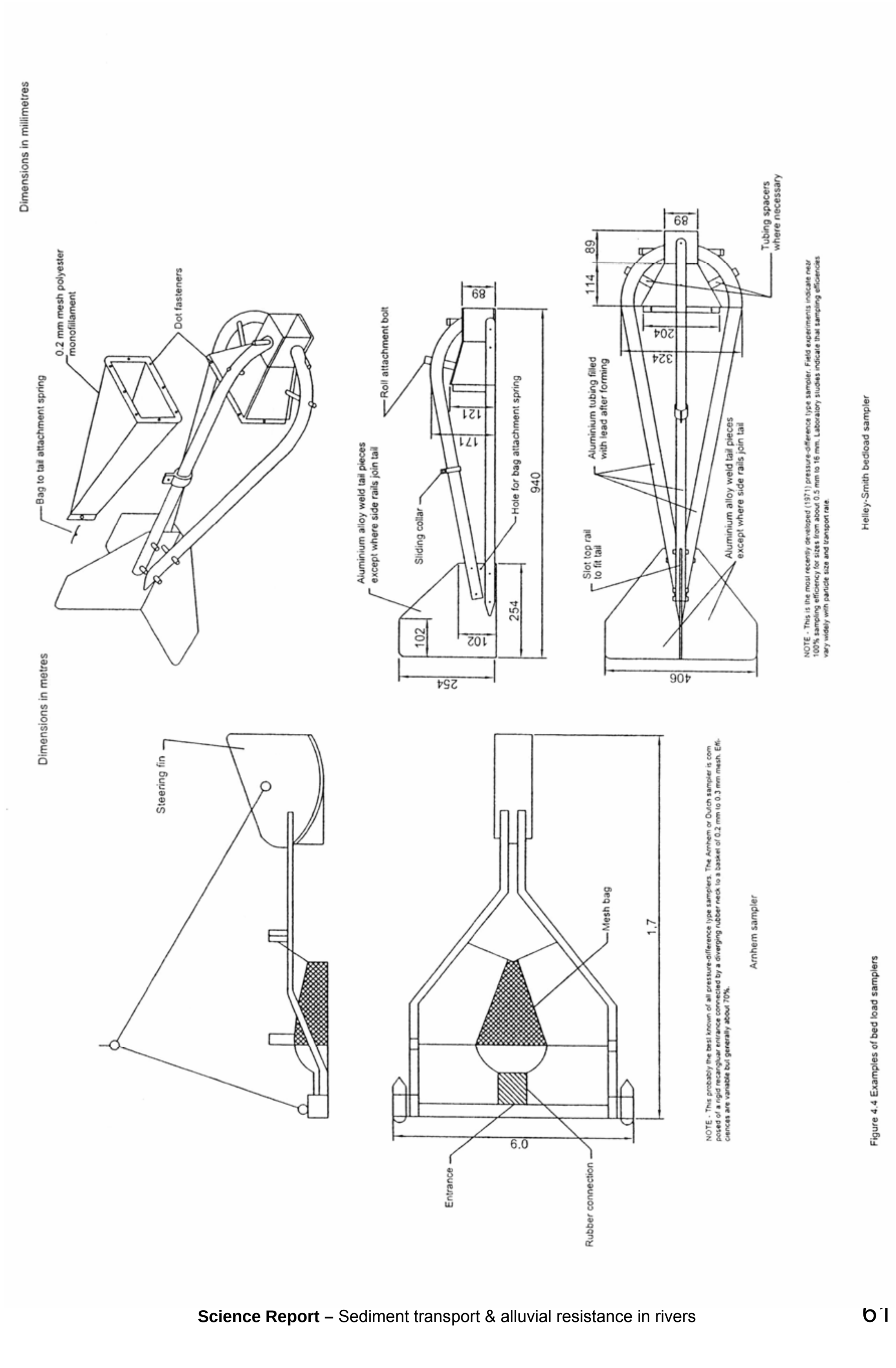
In uni-directional flow particle sizes and concentrations vary with height above the bed though the very fine material is usually distributed fairly evenly through the depth. The size of the bed material particles is a minimum at the surface and a maximum close to the bed and the concentrations vary in a similar manner. Because of these variations it is necessary to sample at several points in the cross-section.
Suspended sediment samples comprise a mixture of sediment and water and their difference in density means that extreme care must be taken in the sampling process. Any accelerations or decelerations as the fluid / sediment mixture approaches the sampler cause sampling errors and much effort has been expended in the design of samplers to avoid these effects.

There are three basic categories of sampler with many proprietary variations within each category:-

- *Integrating samplers:* These accumulate a water-sediment mixture over a period of time by withdrawing it from the ambient flow through a relatively small nozzle. These samplers can be used in a fixed position or can be lowered through the fluid to gain a measure of conditions throughout the depth.
- *Instantaneous or grab samplers:* These take the form of an open ended tube, both ends of which are closed simultaneously, thus trapping a finite volume of the sediment / water mixture. These are point samplers and are normally deployed in

numbers so that time-coincident readings can be obtained at various locations within the flow.

Figure 4.4 Types of bed load sampler



- *Pump samplers:* Pump samplers withdraw the sediment / water mixture from the flow and either store it in containers or filter it. They have the advantage of being able to have large sample volumes, thus getting a better measurement of average conditions. Care must be taken to ensure that the sampler draws water and sediment from the flow at a velocity comparable with that of the flow.

The International Standards Organisation (1977) has published a Standard dealing with the measurement of suspended sediment. This document is rather dated and does not include information on recent developments, particularly concerning the use of pump samplers.

4.4.2 Sediment in reservoirs

Periodic surveys of reservoirs are made to collect data on the volume and location of sediment deposits, the density of the deposits and other characteristics such as particle size grading.

Changes in water depths, with a correction for any changes in water surface elevation, at established measuring sites or along established range lines when compared with previous surveys provide information on both the volume of sediment accumulation and the location of the sediment deposits. The number and location of the range lines depends on the reservoir shape and the precision required.

The type of equipment used for conducting reservoir surveys is described in ASCE (1975). Lawrence (1996) provides an update with additional information on recently developed measurement techniques.

4.4.3 Alluvial Resistance

Measuring channel roughness

There are several techniques that are available to assess the general roughness of channels. These include photographing the reach to identify its physical features, measuring physical properties such as channel dimensions and slope. These data can then be interpreted in terms of roughness coefficients and used in a variety of predictive techniques. More details of this general approach are given by Fisher (1996). The emphasis in this manual is, however, not on general assessments of channel resistance but on alluvial resistance associated with river bed sediments.

Measuring bed roughness

As described in Chapter 3 there are two aspects to bed roughness. The first is the grain roughness that is associated with the sediment particles resting on the surface of the bed and the second is the consideration of bed forms such as ripples, dunes and antidunes.

Recently photogrametric methods have been used to determine the size and shape of gross bed features. This method is still under development but holds out the prospect of the rapid determination of bed features that are exposed above the water surface.

In many respects the measurement of bed roughness is of limited practical value because of the grave difficulty in converting the measured roughness characteristics into a measure of hydraulic resistance which can be used in predictive equations. The exception is where there is a flat but grainy bed, such as can be found in certain gravel rivers. Here a measure of the grain sizes found on the surface of the bed can be used to determine the equivalent Manning or Colebrook and White roughness coefficient.

For the specific case where the bed is generally flat and, where the sediment size is large, the surface texture should be measured as described above. The D_{84} or D_{90} size of the surface material is of particular value in determining the flow resistance of the bed.

4.5 Analysis of Data

4.5.1 Introduction

Sediment data is sometimes used directly to assess a problem. Measurements of deposition in a reservoir over a period of time, for example, can be used directly to assess the inflow of sediments and the likely lifespan of the reservoir. In other cases, the data forms an input to more sophisticated analyses which may involve, for example, computational modelling.

In either case careful examination of the data should be carried out in order to check consistency and to remove obvious anomalies. Graphical and regression analyses are helpful in this respect.

The detailed methods for analysing the various types of raw data, the acquisition of which is described in Section 4.4, are beyond the scope of this manual. The approach is, therefore, to describe the broad principles and then make reference to relevant texts.

4.5.2 Sediment in rivers

Analysing bed material samples

Sediment size is the most commonly used parameter to designate the properties of individual particles. Since particles of natural sediment can be irregular in shape, a single length or equivalent diameter has to be chosen to characterise the size. Four such diameters, ie nominal diameter, projected diameter, sedimentation diameter and sieve diameter are used for different particle sizes or purposes.

Sieve diameter is commonly used for medium to coarse particles and this is determined by passing the mixture through a battery of sieves of progressively finer mesh size. Sedimentation diameter is commonly used for fine materials and this is determined by measuring fall velocities and converting these to size using established relationships between the two parameters.

Further details on methods for the determination of concentration, particle size distribution and relative density are given by the International Standards Organisation (1985). There are special techniques for gravel bed rivers, see International Standards Organisation (1992c).

Analysing transport rates

A method of computing total transport rates (bed material load plus wash load) from direct measurements of bed load and suspended load is given by the International Standards Organisation (1992a).

Note: This Standard refers to the “calculation of bed load”. The method described, however, clearly includes all material collected by bed load and suspended load samplers. The procedure thus gives an estimate for the rates of transport of all sediments whether they are fine and cohesive travelling in suspension or whether they are coarser and non-cohesive travelling either in close proximity to the bed or in suspension. The method described determines the total transport rates for different size fractions of the sediment taking into account:-

- the efficiency of the bed load sampler
- the tendency, if any, of the bed load sampler to collect a proportion of the suspended load
- the efficiency of the suspended load sampler
- the unmeasured fine material which travels below the level of the suspended load sampler and is not caught by the bed load sampler

If, as is the case in most engineering applications, it is necessary to separate the wash load (fine, cohesive sediments) from the bed material load (coarser non-cohesive sediments) the best approach is as follows:-

Wash load:

- analyse the suspended load samples for fine material less than 60 microns and determine the concentration by dry weight of the different size fractions

- multiply the mean concentration by the mean flow, either using vertical segments or by considering the cross section as a whole

Bed load:

- take the direct measurements of the bed load as determined by the bed load sampler and make allowance for the efficiency of the particular type of sampler being used (if known)

Note: The determination of bed load transport rates using samplers is extremely difficult and the answers obtained are often subject to gross errors. It is often more accurate either to compute the bed load transport rate using one of the methods derived for that purpose or to measure the suspended bed material load and to add a small proportion of this load to take into account the bed load. Typically, the bed load transport rate will be between 5 and 10% of the suspended load.

Suspended bed material load:

- analyse the suspended load samplers for coarse material greater than 60 microns and determine the concentration by dry weight of the different size fractions
- Divide the cross-section into a number of areas or segments and determine the transport rates for each size fraction through each area by multiplying the local concentration by the discharge passing through the area
- Sum the transport rates for each size and each area to gain a knowledge of the total bed material transport and the distribution of the sediments within the cross-section

Total bed material load:

Add the suspended bed material load to the bed load.

4.5.3 Sediment in reservoirs

Analysing deposition

The method adopted for computing sediment volumes from survey data depends on mostly on the survey method that has been used. For range line surveys the constant factor method, Burrell (1951), has been widely adopted.

The Stage width modification method, Lea (1991), is a development of the constant factor method, and exploits the close relationship between stage-width and stage-area curves. Its performance is substantially better than the constant factor method when pre impoundment data is sparse. The method makes better use of sparse input data both in calculating the original reservoir volume and in coping with an erratic sediment distribution.

It is recommended that the stage width modification method is used to compute sediment volumes. As hand calculations using the procedure would be very time consuming, calculations are best carried out using software package such as SWIMM developed by HR Wallingford. Computations are based on the data collected from a range line survey, with cross sections and contour areas derived from pre-impoundment maps or surveys. The software computes the storage volume for a range of water levels at the time of pre impoundment and first or later surveys, and estimates the volume of sediment deposits from the differences in water volumes.

4.5.4 Alluvial Resistance

Analysing alluvial resistance

Field measurements of the grain and form roughness of river beds are only of real value in one specific case ie the determination of the hydraulic resistance of plain bed with significant grain roughness.

In this case the surface sample of the bed material should be analysed and the D_{90} size determined. Use should then be made of the Colebrook and White rough turbulent equation:-

$$V = 4\,(2\,g\,d\,S)^{1/2}\,\log_{10}(14.8\,d / k), \tag{4.1}$$

where d is the depth of flow (m)

g is the acceleration due to gravity (m/s^2)

k is the effective roughness height (m)

S is the energy gradient

V is the mean velocity of flow (m/s) and

$$k = 3\,D_{90}, \tag{4.2}$$

where D_{90} is the sediment size for which 90% of a surface sample is finer (m)

It should be noted that some authors have selected the D_{84} size and others the D_{90} size to characterise the surface roughness. In most practical applications the difference that this makes is negligible.

Because of the difficulty in converting information on measured bed forms into hydraulic resistance coefficients, general predictive techniques have been developed which determine alluvial resistance from the sediment properties and the ambient flow conditions, thereby circumnavigating the need for measurements of bed forms. These techniques are the subject of Chapter 8.

5 Initiation of Motion

5.1 Introduction

It has been found empirically that for very low flows no sediment motion takes place. If the flow is gradually increased then the hydrodynamic forces on individual particles will eventually become sufficiently large that the particles begin to move. The point at which sediment movement takes place is of interest for a number of problems. If the flows are always below the threshold of motion then no movement or change to the bed profile can be expected. Thus if the flows can be shown to be always below the threshold of motion then all the other aspects of mobile-bed hydraulics can be ignored. As discussed in Chapter 9 the amount of fine sediment that is present in gravel affects the survival of fish eggs. There is thus interest in knowing the flow conditions in which fine sediment will be deposited or the flows needed to ‘clean out’ fine sediments from gravel. The theoretical approach to initiation of motion is also applicable to the estimation of the size of stone rip-rap that will remain stable under given flow conditions.

A particle that rests on the bed of a channel in a flow is subject to a number of forces. It is subject to:

- gravity, acting vertically downwards,
- reaction forces from the other sediment particles in contact with the given particle,
- drag force, arising from the hydrodynamic forces on the particle,
- lift force, arising from the hydrodynamic forces on the particle,

A sediment particle will move when the hydrodynamic forces exceed the gravity and reaction forces, see Figure 5.1.

Due to the turbulent nature of most natural flows, the hydrodynamic forces are not constant but vary in time, see Figure 5.2. The relative positions of particles means that in any sediment bed the reaction forces on the particles vary from particle to particle. This implies that there is not one unique flow condition that separates sediment motion from non-motion. At a certain flow a single particle will move. At larger flows a few particles will move occasionally and for even larger flows general sediment motion will take place. This has led to a number of criteria for initiation of motion.

5.2 Initiation of Motion in Uniform Sediments

5.2.1 Criteria for initiation of motion

A number of different criteria for initiation of motion have been suggested:

- a single particle moving,
- a few particles moving,
- general motion of the bed,

- limiting condition when the rate of sediment transport tends to zero.
- a low but defined sediment transport rate.
- The use of each criteria will lead to slightly different flow conditions for initiation of motion.

Figure 5.1 Forces acting on a sediment grain

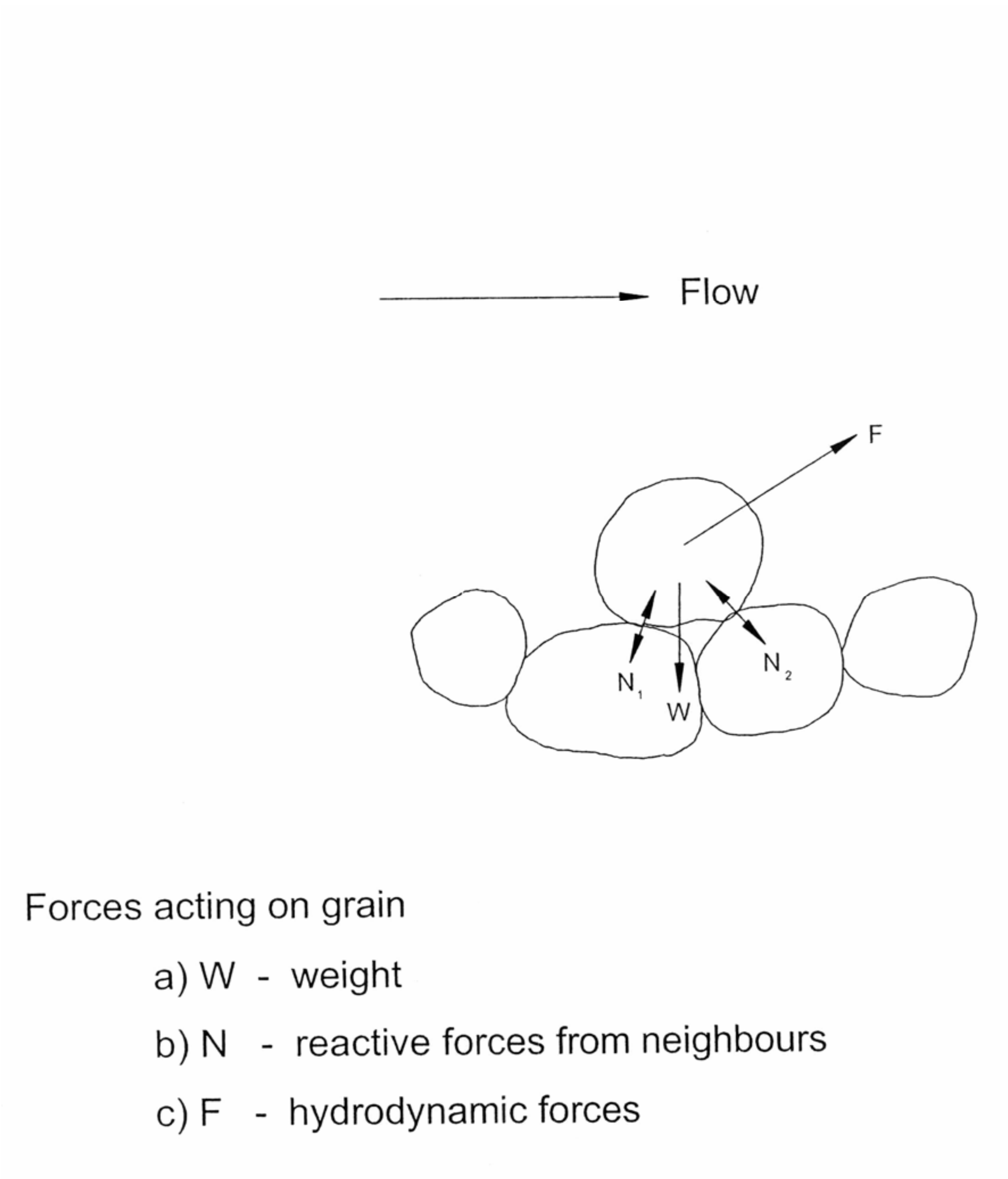
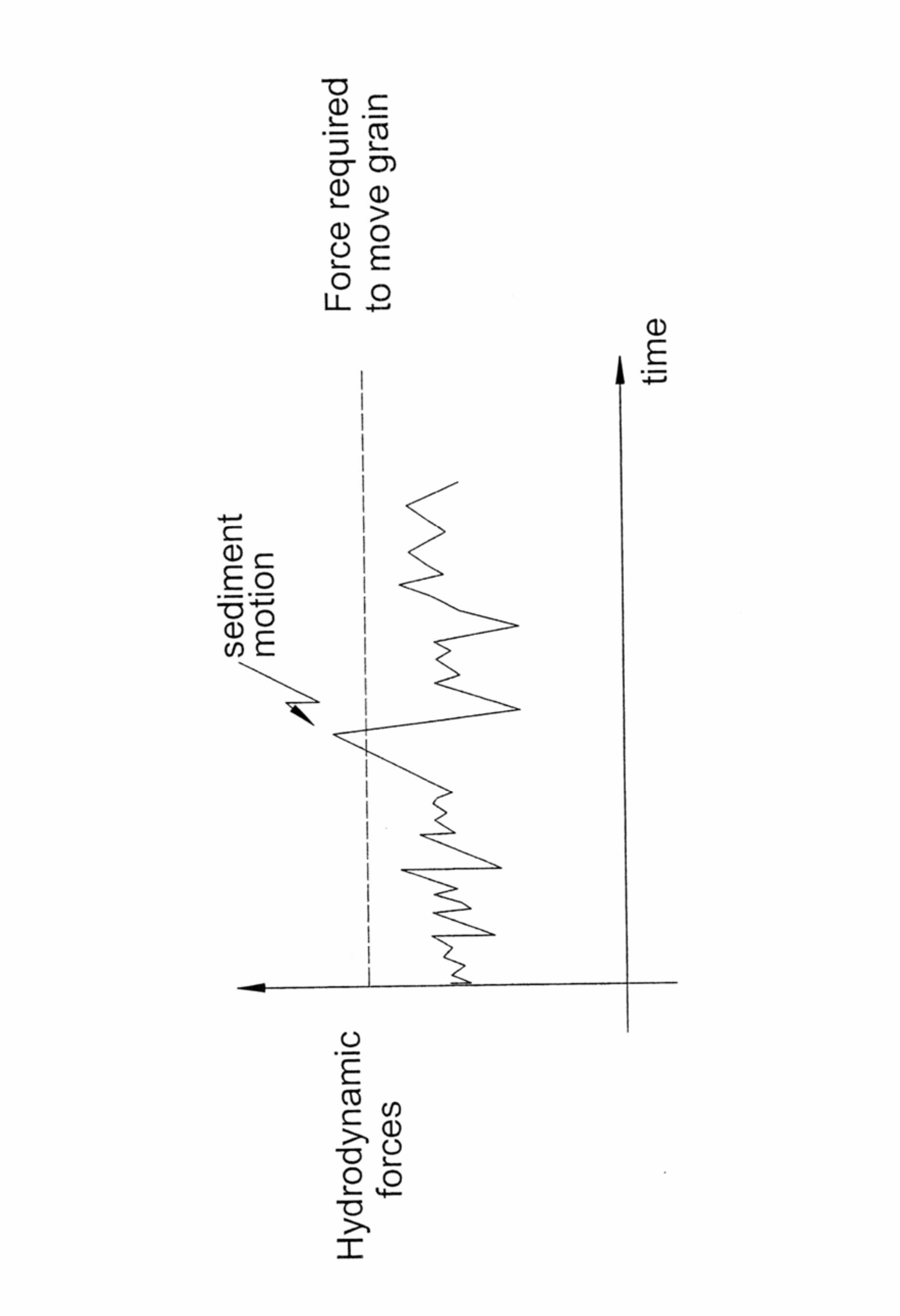


Figure 5.2 Hydrodynamic forces on a sediment grain as a function of time



5.2.2 Critical shear stress (Shield's curve)

The most useful and apparently the most rational approach to initiation of motion has been based on the concept of a critical shear stress (Yalin 1977). This assumes that there is a relationship between the shear stress applied by the flow to the bed and the movement of sediment particles and that initiation of motion can be assumed to occur when a critical shear stress is reached.

Shield derived an empirical relationship between a non-dimensional shear stress, called the Shield's parameter, and a non-dimensional sediment size, called the Particle Reynold's number, see Figure 5.3.

5.2.3 Critical velocity

It is difficult to measure shear stress directly and so it would be attractive to be able to define the critical conditions for initiation of motion in terms of the flow velocity as this would be easy to apply in practise. Many authors have studied this problem, including Hjulstrom (1935) and Neill (1967), see Figure 5.4. As the flow velocity varies through depth one problem is associated with the depth at which the velocity is considered. A further problem relates to the relationship between critical shear stress and critical velocity. The relationship between velocity at a particular depth and shear stress depends upon the depth and the hydraulic roughness of the surface and so there is no unique relationship between critical shear stress and velocity. It appears that for a given sediment size there are a range of possible critical velocities depending upon the other flow conditions. Thus though the concept of a critical velocity may be useful, in practise it should be used with extreme caution.

Neill equation

$$\frac{V_c^{\,2}}{\left(\rho_s/\rho - 1\right) g\, D} = 2.0\left(\frac{D}{d}\right)^{-1/3} \qquad (5.1)$$

This equation should only be used within the parameter range indicated in Figure 5.4. Due to the limitations discussed above it is best to only use it to provide an order of magnitude estimate of the critical velocity. Wherever possible Shield's equation based on critical shear stress should be used in preference.

5.2.4 Recent developments

Recent work by McEwan and Heald (2001) has illustrated that the notion of a particular flow at which all sediment of a particular size will begin to move is a simplification. In reality there is a range of shear stresses at which particles of a given size will begin to move. Meanwhile the shear stress itself also varies both temporally and spatially due to the turbulent characteristics of the flow.

Figure 5.3 Shield's curve

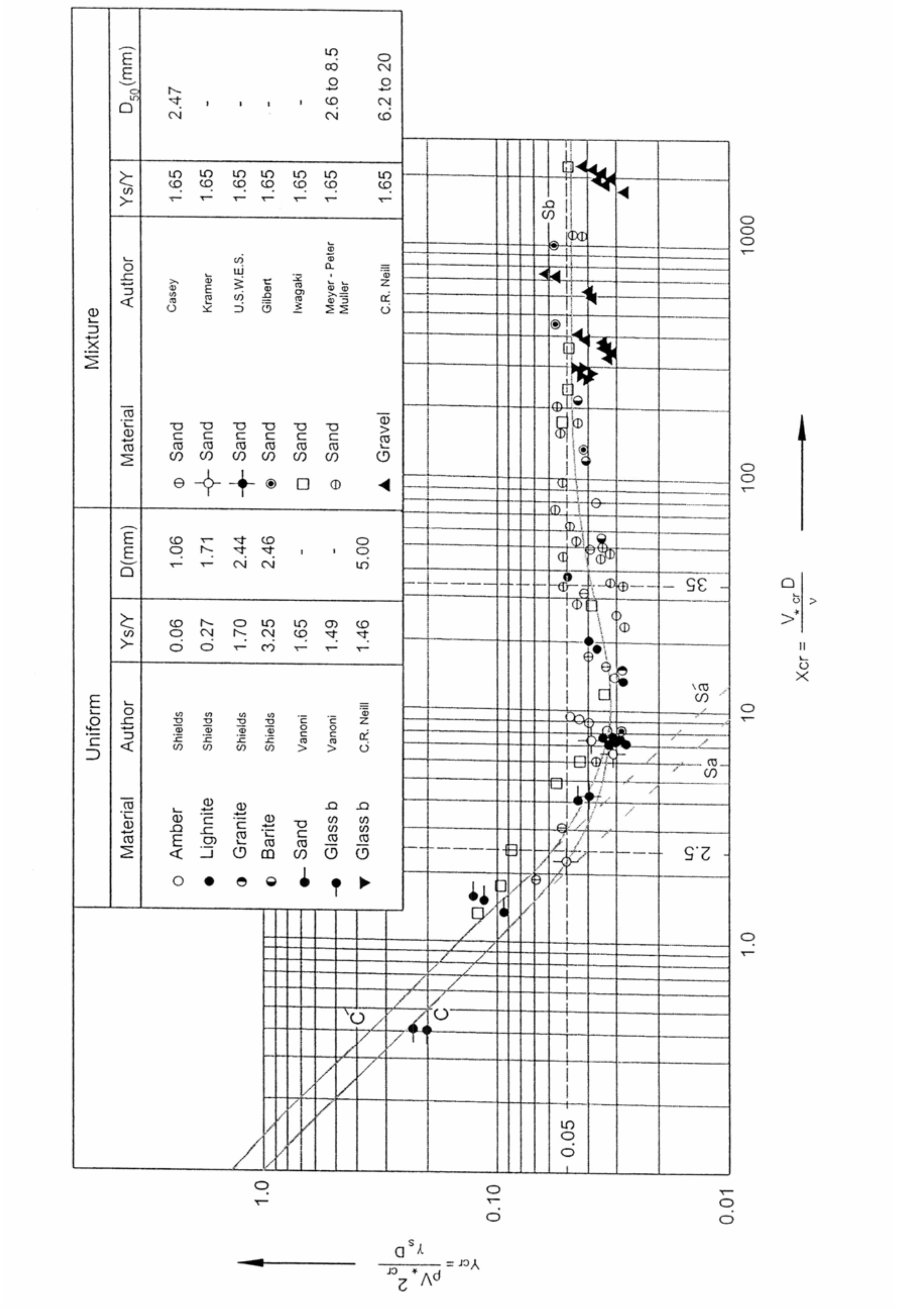
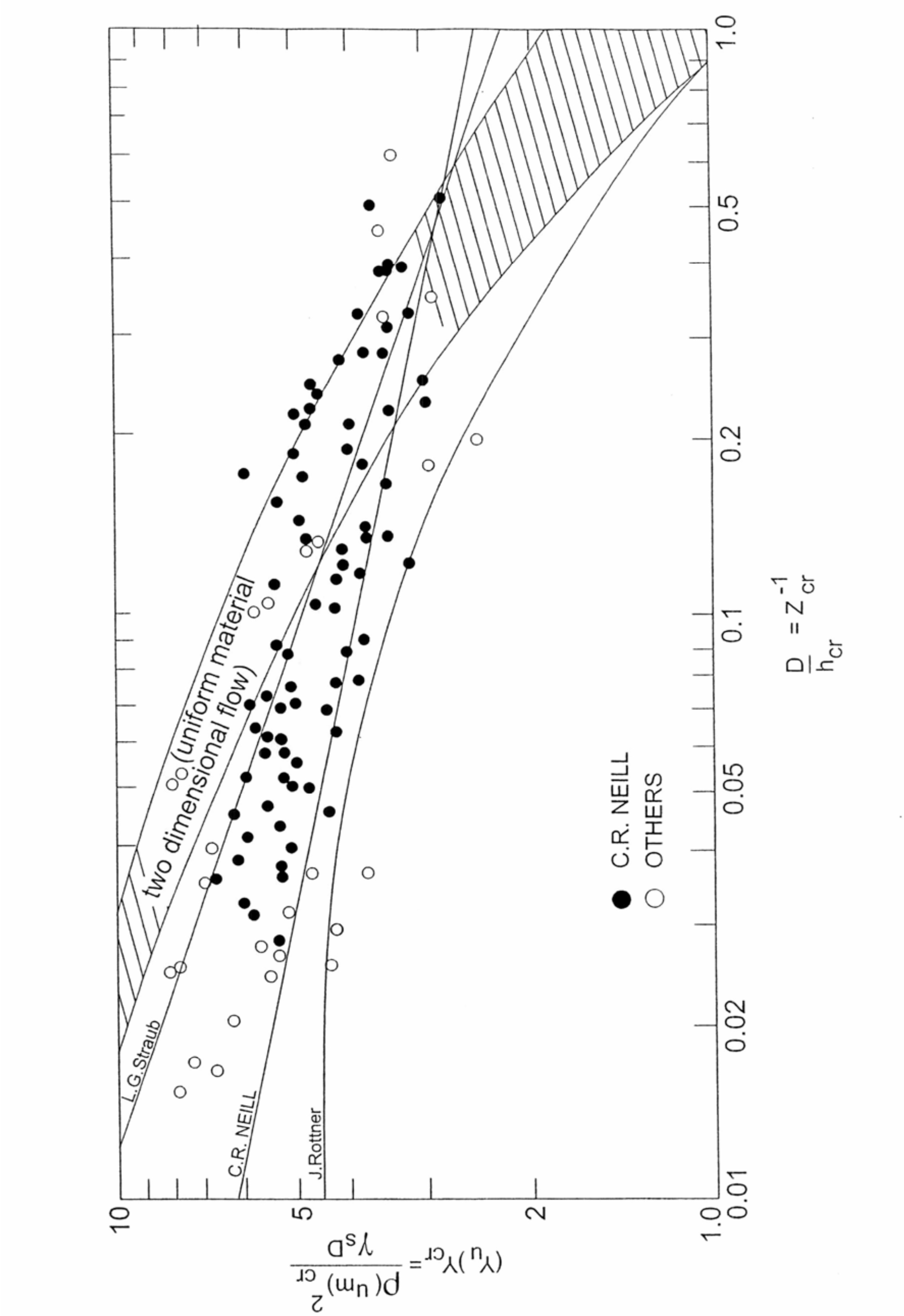


Figure 5.4 Critical velocity



5.3 Initiation of Motion for Non-Uniform Sediments

5.3.1 Selection of representative sediment diameter

The approaches described above can be used if the sediment is relatively uniform, for example if D_{84}/D_{16} is less than 1.5. If a wide range of sediment sizes are present then a number of difficulties arise as the use of a single representative sediment diameter will no longer adequately describe the behaviour of the sediment. If, for example, the D_{50} size is taken as a representative sediment size then the finer fractions of the sediment will start to move for flow conditions when the initiation of motion criteria suggest that no motion will take place. Meanwhile when the initiation of motion criteria suggests that the D_{50} size will be in motion the coarser fractions may not be moving, see Figure 5.5. In these cases calculations have to be performed for a range of sediment sizes to determine under a given flow condition which size fractions are moving.

In flows in which only some of the sediment sizes are capable of being moved then selective sediment transport may take place. In these situations, depending upon the sediment supply from upstream, the smaller sediment sizes may be removed leaving behind the coarser sediment fractions. This can lead to a change in the composition of the surface sediment. Where the surface of a river bed is covered with a coarser surface layer of sediment it is described as being armoured. This is observed most frequently in gravel bed rivers.

5.3.2 Hiding functions

There is, however, another, and technically more difficult, problem associated with widely graded sediments. The presence of the different sediment sizes within the mixture alters the behaviour of the sediment. Thus sediment of a particular size will behave differently in a mixture than it would in a uniform sediment of the given size. In general, in a mixture the finer sediment becomes more difficult to move than it would in a uniform sediment, that is, the critical shear stress increases, while the coarser fractions become easier to move, that is, the critical shear stress reduces.

These effects are normally described in terms of the smaller fractions ‘hiding’ in the lee of the larger sediments while the larger sediments are more exposed to the flow as they are unable to ‘pack’ as well into the bed due to the presence of the finer sediment. The original studies identified the ‘hiding’ of the finer fractions first and the correction factors that were developed to describe this effect were called ‘hiding factors’. The name is now commonly used for expressions which describe both hiding and exposure.

For initiation of motion, factors are used to modify the critical value of shear stress to take account of these sediment grading effects, see Figure 5.6. In general the hiding factors that are used are specific to the particular theory or approach being used. Thus hiding factors for Shields equation cannot be used in conjunction with, for example, an equation for critical velocity. The hiding functions that are given in the literature are, in general, based on limited laboratory data and their use for field situations, therefore, normally requires considerable extrapolation. The results obtained should thus be treated with suitable caution.

Figure 5.5 Difficulty of selecting a single representative sediment diameter for a graded sediment

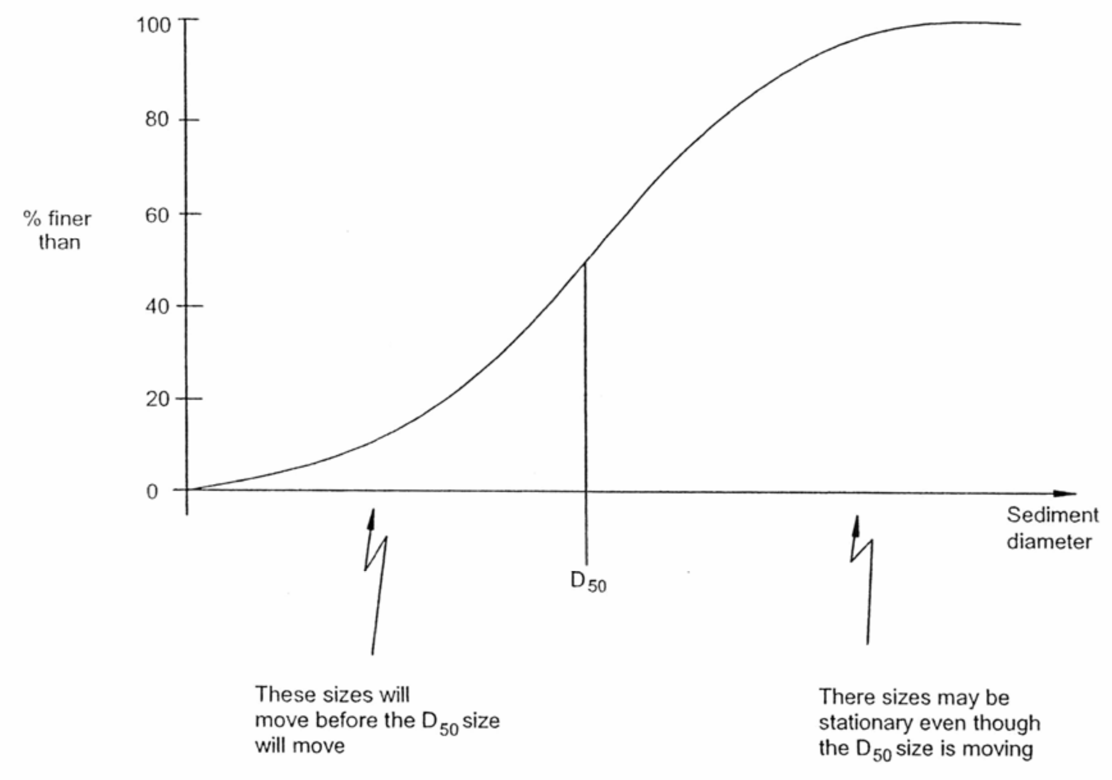
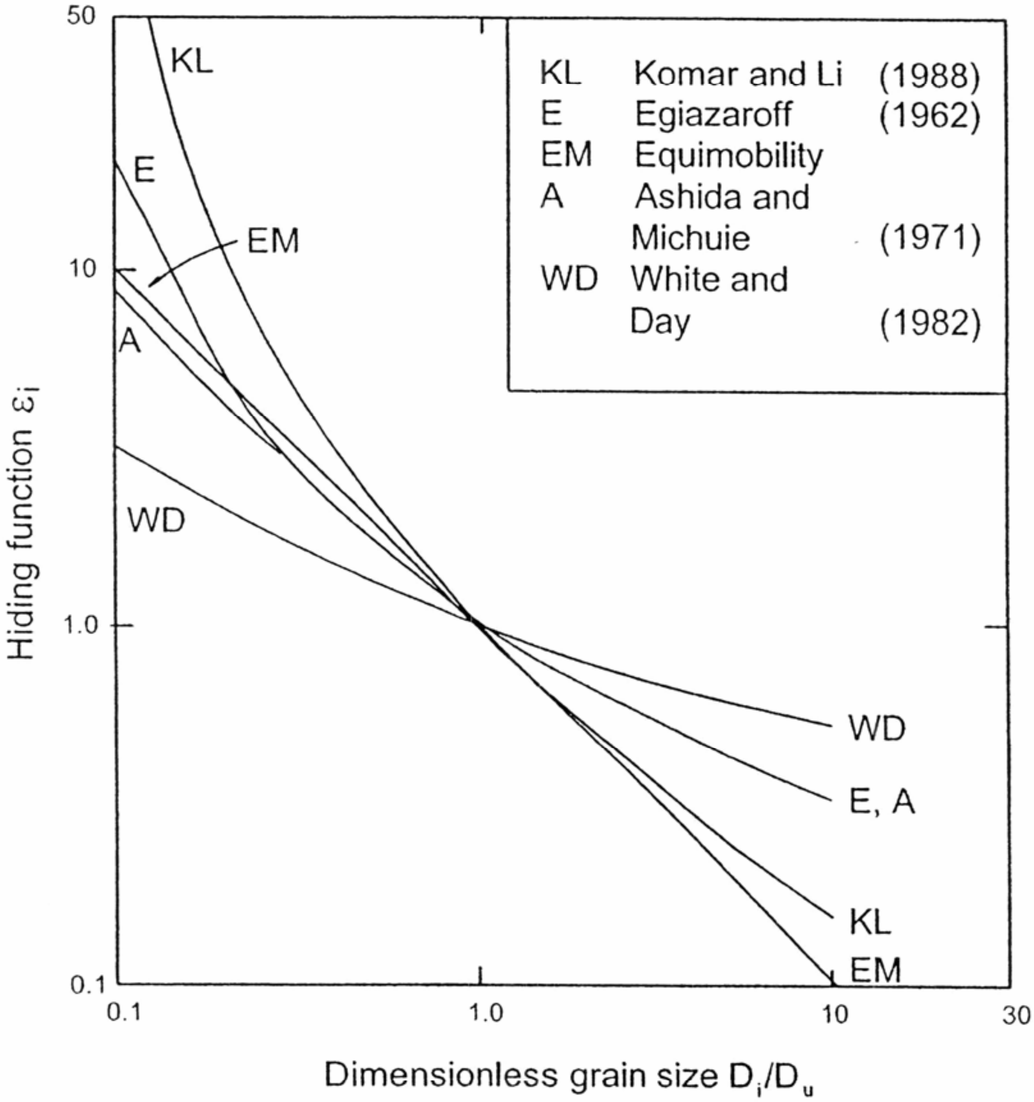


Figure 5.6 Hiding function as a function of dimensionless grain size



Ferguson et al (1989) derived a simple hiding function for the Shield's relationship. They postulated that the threshold for entrainment of size D_i in a mixed size gravel bed of median size D_b was given by the expression

$$\tau_{ci}^{*} = (aD_i / D_b)^{-b} \tag{5.2}$$

where a is the critical shear stress for size D_b, $\tau_c^* = \tau_c/(\rho_s-\rho)gD$ and τ_{ci}^* is the value of τ_c for sediment of diameter D_i. Field measurements suggested the equation:

$$\tau_{ci}^{*} = 0.047(D_i / D_b)^{-0.88} \tag{5.3}$$

It has been suggested that the exponent b is a function of D_{84}/D_{16}. It would seem that in reality the coefficients should depend upon the full grading curve rather than isolated parameters such as D_{84} and D_{16}. Thus in reality the coefficients are probably functions of $\int p_i D_i$.

Table 5.1 shows the impact of the Ferguson et al hiding function on critical shear stress. It can be seen that for sediment sizes significantly smaller than the median value, the value of the Shield's parameter is increased significantly while for the sizes significantly larger than the median the value of the Shield's parameter is reduced significantly. This has a tendency to equalise the shear stresses at which the different sediment sizes move. This concept is known as equi-mobility.

Table 5.1 implies that the shear stress required to move the smallest, 0.004m size sediment is 4.12 times that required to move that same sediment in a uniform bed consisting entirely of 0.004m size sediment. Meanwhile the shear stress required to move the coarsest, 0.10m size sediment is only 0.24 times that required to move that same sediment in a uniform bed consisting entirely of 0.10m size sediment.

These figures are for illustration only as the Ferguson et al equation is based on limited field data and it should only be used with caution.

Table 5.1 Impact of Ferguson et al hiding function on critical shear stress

(D_b = 20 mm)

D_i (m)	$\frac{D_i}{D_b}$	$\left(\frac{D_i}{D_b}\right)^{-0.88}$	τ_{ci}^*
0.004	0.2	4.12	0.194
0.01	0.5	1.84	0.0865
0.02	1.0	1.0	0.047
0.04	2.0	0.54	0.025
0.10	5.0	0.24	0.011

White and Day (1982) analysed the results of a sequence of laboratory experiments involving partial sediment transport in which some but not all of the sediment sizes were moving. They fitted the Ackers and White sediment transport theory to the results by modifying the threshold of motion parameter A. They defined as D_A, the sediment diameter in a mixture which begins to move under the same flow conditions as a uniform bed material. Their analysis of the data suggested that the value of the threshold parameter A for a sediment diameter D_i in a mixture is given by:

$$\frac{A^1}{A} = 0.4\left(\frac{D_i}{D_A}\right)^{-0.5} + 0.6 \qquad (5.4)$$

where A is the value of A for a uniform sediment of that size. The following equation for D_A was fitted to the data:

$$\frac{D_A}{D_{50}} = 1.6\left(\frac{D_{84}}{D_{16}}\right)^{-0.28} \qquad (5.5)$$

It is of some concern that as D_{84}/D_{16} tends to 1 the value of D_A does not tend to D_{50}.

One can eliminate D_A between equations (5.27) and (5.28) to obtain:

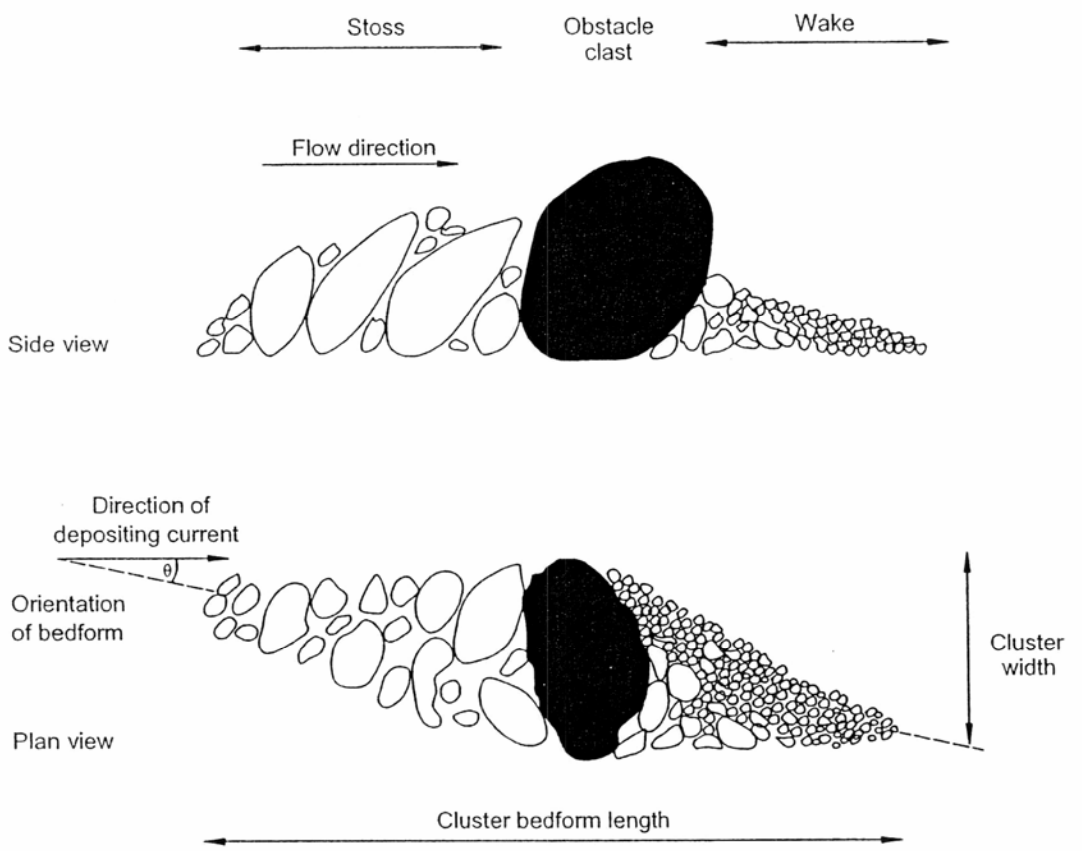
$$\frac{A^1}{A} = 0.32\left(\frac{D_i}{D_{50}}\right)^{-0.5}\left(\frac{D_{84}}{D_{16}}\right)^{0.14} + 0.6 \qquad (5.6)$$

This suggests that the parameters in equation (5.3) may vary with the sediment grading rather than being constants.

There is also experimental and field evidence to suggest that at very low sediment transport rates the sediment particles on the bed become arranged in such a way that they become more stable than they would be in a random configuration. In experimental studies it is observed that the particles appear to become arranged in characteristic patterns on the bed, for example, the larger sediment particles have been observed to occur in a diamond pattern on the bed. The development of these patterns, which have been referred to as bed texture, have been accompanied by significant increases in hydraulic roughness. In the field, particle clusters have been observed in which particles with a range of sizes become arranged around individual large particles. This can provide a stability in excess of that which would be possessed by the constituent particles in isolation, see Figure 5.7. As yet there are no generally applicable methods to assess the impact of bed texture or cluster formation on the initiation of motion.

The issue of hiding also arises when one considers sediment transport.

Figure 5.7 Archtype pebble cluster



5.4 Influence of History of Flows on the Initiation of Motion

There are observations to suggest that if there is a prolonged period with no sediment transport then the bed material can become consolidated and hence more difficult to move. The infiltration of fine, cohesive sediment can create a significant binding effect. This can be particularly evident in arid or semi-arid streams in which the sediment has had an opportunity to dry out. Though this effect has been observed in the field (Reid and Frostick 1984 and Reid et al 1985) there is no method available to take it into account in predicting initiation of motion.

5.5 Depth/Diameter Effects

Experimental evidence suggests that for small depth diameter ratios the conditions for initiation of motion are modified (Bettess, 1984). If the depth is less than ten times the diameter then the critical value of the Shields parameter increases as the depth-diameter ratio reduces, see Figure 5.8. Thus if in a gravel river the ratio d/D is 3 then the value of the Shield's parameter that should be used is 0.07 rather than 0.05.

In practise these conditions only occur in gravel bed rivers. It is thought that the effect is due to the fact that at small values of the depth diameter ratio the turbulence in the flow is altered and damped and this reduces the hydrodynamic forces on the sediment particles.

6 Prediction of Sediment Motion

6.1 Introduction

This chapter deals with the prediction of sediment transport rates. It follows the descriptions given in Chapter 3 dealing first with bed load, then total bed material load and finally wash load. Examples are given which provide step-by-step instructions on the calculation procedures and also illustrate the sensitivity of the results to the methods used and the values of the relevant parameters that are substituted into the equations.

Sections 6.1 to 6.5 deal with the most common situation where the sediment grading curve shows only a very limited range of sizes and where the transport rate can be calculated in one step from one or two specified diameters eg D_{35} or D_{50} plus D_{90}. Sections 6.6 and 6.7 deal with the more complex situation where there is a wide range of sediment sizes present in a bed sample, typically found in rivers in upland areas, and where a more complex calculation procedure has to be adopted.

6.2 Bed Load Transport Rates

Bed load transport formulae are applicable when the movement of sediment is close to the bed. This is generally the case in water courses with coarse sediments such as gravel rivers and mountain streams. Qualitatively this is usually when (v_*/ω) is less than approximately 1, see Figure 3.6. The use of bed load transport formulae in other circumstances is likely to underestimate the sediment transport rate as they do not take into account the more complex phenomena associated with the transmission of sediments in suspension.

One predictive technique which was developed for coarse sediments and which has been shown to give reasonable answers for sizes in excess of about 5 mm is the Meyer-Peter and Muller (1948) formulation. This predictive technique is described in Appendix 2.

6.2.1 The bed load formulae of Meyer-Peter and Muller

The Meyer-Peter and Muller formula relates the bed load transport rate to the discharge, the water surface slope, S, the specific gravity of the sediment, s, and the sediment diameter, D. The equation is dimensionally homogeneous and may be used with any consistent set of units.

The equation was based on laboratory data with sediments in the size range 5 to 28 mm. See Appendix 2 for details.

6.3 Transport Rates for the Total Bed Material Load

Formulae have been developed for predicting the total bed material transport and these have proven extremely useful. The formulae predict the total bed material transport under most conditions, including those in which the transport is predominantly as bed load. The one disadvantage of the total bed material formulae is that they do not explicitly distinguish between the different modes of transport and hence it is not possible to assess the distribution of the sediments, that is, the amounts travelling close to the bed and the amounts in suspension.
Two formulae for the prediction of total bed material transport are recommended. The predictive technique of Engelund and Hansen (1967) is extremely simple to use and gives good results over a wide range of conditions. It does suffer the one disadvantage that fluid viscosity is not taken into account and hence predictions of low transport rates close to the threshold of movement can be suspect.

The Ackers and White (1973 and 1992) technique is reliable and of general application. It has been shown to agree well with laboratory, including lightweight sediments, and field data over a wide range of conditions. The theory assumed that the quantity of fine, non-cohesive bed sediments travelling mainly in suspension correlated with total boundary shear stresses and that the quantity of coarse, non-cohesive bed sediments travelling mainly as bed load correlated with grain shear stresses. Sediment size was defined in terms of the non-dimensional parameter, D_{gr} :-

$$D_{gr} = D\,[\,g\,(s - 1)\,/\,\nu^2\,]^{1/3} \qquad (6.1)$$

where D is the representative sediment diameter (m)

s is the specific gravity of the sediment

The data suggested that fine sediments were in the range $D_{gr} \sim 1$, that is, sand sizes less than 0.04mm. Coarse sediments were in the range $D_{gr} > 60$ ie sediment sizes in excess of approximately 2.5mm. Intermediate sizes were termed “transitional” and the relative influences of total and grain shear were established in terms of D_{gr}. D is selected to be a representative sediment diameter. Depending upon the particular application different sediment diameters may be selected.

Sediment movement is predicted in terms of a sediment mobility number based on the ratio of shear stresses to immersed weight of the sediment particles. The form of the mobility number was set up such that only the relevant shear forces were used, that is, total shear for fine sediments, grain shear for coarse sediments and an intermediate value for transitional sediments depending upon D_{gr}.

6.4 Wash Load Transport Rates

There are no predictive techniques for wash load transport rates in water courses which are based on local flow and sediment parameters. The previous two sections have dealt with non-cohesive sediments, the transport rate of which is related to local flow conditions. In practice, sediments less than about 0.06 mm in diameter are cohesive and do not behave in the same way as the bed material load. Rivers normally have the capacity to transport as much of this fine sediment as the adjacent interfluvial areas are capable of supplying.

Approximate estimates of the total quantity of sediment carried by a river can be made by estimating the sediment yield of the catchment upstream or by taking long term measurements of suspended load in the river and building up an approximate sediment rating curve. Sediment transport derived by either of these methods will include all the sediment sizes that are to be found in suspension. This means that the results are a mixture of locally determined transport, comprising the non-cohesive sizes, and the supply generated transport, comprising the cohesive sizes.

6.5 Example Calculations of Sediment Transport Rates

6.5.1 Bed load transport

Bed load transport, without significant quantities of bed material in suspension, occurs mainly at low transport rates especially with coarse sediments. The Meyer-Peter Muller formulae is recommended for use under these conditions although both the Engelund and Hansen and the Ackers and White total load formulae will predict bed load under these circumstances (since the bed load approximates to the total bed material load).

At higher transport rates bed materials travel in significant quantities in suspension. Under these circumstances the Meyer-Peter Muller formulae will give only the bed load component of the total bed material load.

Example calculation:

A water course has a width of 40 m and a longitudinal slope of 0.005. The bed material has a D_{50} size of 5.5 mm and a D_{90} size of 45.0 mm. The Manning roughness of the channel has been estimated as 0.032. Calculate the bed load transport rates for depths of 0.5 m, 0.71 m and 0.98 m.

Use the Manning formula to determine the mean velocities of flow, V (m/s), and continuity to determine the discharges, Q (m^3/s).

$V = (\ 1/n\ )\ d^{2/3}\ S^{1/2}$ = 1.392, 1.758, 2.180 m/s for depths of 0.5, 0.71 and 0.98 m respectively

Q = V b d = 27.8, 50.0 and 85.4 m^3/s for depths of 0.5, 0.71 and 0.98 m respectively

The bed form roughness factor is given by equation 6.6:-

$k_s = 0.3 \times (32.1\ n)^6 = 0.35$ m

The calculations, in accordance with Section 6.1.1, can be tabulated as given in Table 6.1.

Table 6.1 Bed load transport rates using the formulae of Meyer-Peter and Muller

d (m)	F_s	C_0	C_1	μ	g_b (T/s/m)	q (m^2/s)	X (ppm)
0.50	0.275	11.7	38.2	0.169	zero	0.557	zero
0.71	0.391	14.4	41.0	0.209	0.000085	0.998	85
0.98	0.540	17.0	43.5	0.243	0.000322	1.709	188

The results show no movement of the bed material at a depth of 0.5 m. Bed load concentrations increase as the depth and flow increases.

The parameter C_0 is the overall Chezy coefficient and C_1 is the grain related Chezy coefficient. The parameter C_1has been introduced to take account of the fact that in a bed with bed features not all the applied shear stress acts on the grains of the bed and contributes to sediment movement. As can be seen from Table 6.1 the introduction of this factor can have a significant impact on the calculated sediment transport. It also means that the Meyer-Peter Muller equation may predict no sediment transport when the Shield's equation would suggest that there is sediment movement. It is implicit in the use of the Shield's equation that the bed is plain. The conclusion must be that if the value of the parameter □ varies significantly from 1 then the results should be regarded with caution.

In Section 6.6.1 of this report an example is given in which the same channel dimensions are assumed and the same sediment characteristics. In this example transport rates for the total bed material load are calculated for the depth of 0.71 m. The mean sediment concentration for the total bed material load is estimated to be approximately 330 ppm and, comparing this with the results from the Meyer-Peter Muller analysis, the bed load appears to be approximately 15 to 20% of the total load.

6.5.2 Transport of the total bed material load

Total bed material load formulae are the only type of single formula applicable when significant quantities of bed material are travelling in suspension. This occurs at medium and high transport rates, particularly with medium to fine sediments. The only other option is to calculate the bed load and suspended load separately.

6.5.3 Accuracy of sediment transport formulas

A number of studies have been carried out in which the predictions of sediment transport theories have been compared with observations. In general, the better sediment transport theories give predictions that are within a factor of 2 of the observations approximately 70% of the time. This reflects both the difficulty of predicting sediment movement and the difficulty of measuring it.

6.6 Sensitivity of Calculated Transport Rates to the Quality of the Input Data

The above calculations yield transport rates which have uncertainties associated with the accuracy of the formulae used. In practice there are additional uncertainties associated with the data used in the calculations. Any errors in the estimates of such parameters as depth, roughness coefficients or sediment size increase the overall uncertainty accordingly. It is useful, therefore, to look at the sensitivity of the results to changes in the values of the parameters used as data.

Taking the basic data used in section 6.3 and the results of the Ackers and White formulae it is illuminating to look at the effects of possible measurement or estimation errors in the sediment size, the depth or the Manning roughness coefficient.

6.6.1 Sediment size

The following table shows how the calculated sediment concentrations (and hence quantities) change with the assumed sediment size. Table 6.2 assumes a constant Manning coefficient of 0.030 and a constant depth of 0.98 m.

Table 6.2 Sensitivity of computed sediment transport rates to the assumed sediment size

D_{35} (mm)	**0.30**	0.32	0.34	0.36	0.38	**0.40**	0.42	0.44	0.46	0.48	**0.50**
X (ppm)	**586**	546	512	484	459	**438**	418	401	386	371	**358**
% D_{35}	**-25.0**	-20.0	-15.0	-10.0	-5.0	**0.0**	+5.0	+10.0	+15.0	+20.0	**+25.0**
% X	**+33.8**	+24.7	+16.9	+10.5	+4.8	**0.0**	-4.6	+8.4	+11.9	+15.3	**+18.3**

For this particular example the percentage errors in sediment concentrations, and hence transport rates, are similar to the error in sediment size. This is generally true for sediments larger than about 0.2 mm and for conditions that are well above the threshold of motion. Rates are far more sensitive to the assumed sediment size for fine sediments and/or conditions close to the threshold of motion.

6.6.2 Depth of flow

Table 6.3 shows how the calculated sediment concentrations and quantities change with the assumed depth. The table assumes a constant sediment size of 0.40 mm and a constant Manning coefficient of 0.030.

Table 6.3 Sensitivity of computed sediment transport rates to the assumed depth of flow

d (m)	**0.88**	0.90	0.92	0.94	0.96	**0.98**	1.00	1.02	1.04	1.06	**1.08**
X (ppm)	**399**	408	417	425	434	**438**	451	459	468	476	**487**
V (m/s)	**0.862**	0.875	0.888	0.900	0.913	**0.930**	0.938	0.950	0.963	0.975	**0.991**
Q (m^3/s)	**22.76**	23.63	24.51	25.38	26.29	**27.34**	28.14	29.07	30.05	31.00	**32.11**
Q_s (T/m)	**0.545**	0.578	0.613	0.647	0.684	**0.718**	0.761	0.801	0.844	0.885	**0.938**
% d	**-10.2**	-8.2	-6.1	-4.1	-2.0	**0.0**	+2.0	+4.1	+6.1	+8.2	**+10.2**
% X	**-8.9**	-6.8	-4.8	-3.0	-0.9	**0.0**	+3.0	+4.8	+6.8	+8.7	**+11.2**
% V	**-7.3**	-5.9	-4.5	-3.2	-1.8	**0.0**	+0.9	+2.2	+3.5	+4.8	**+6.6**
% Q	**-16.8**	-13.6	-10.4	-7.2	-3.8	**0.0**	+2.9	+6.3	+9.9	+13.4	**+17.3**
% Q_s	**-24.1**	-19.5	-14.6	-9.9	-4.7	**0.0**	+6.0	+11.6	+17.4	+23.3	**+30.6**

An error in depth measurement affects both flows and sediment concentrations and these errors compound to produce large errors in transport rates. An error of 10% in depth can result in an error of 30% in calculated transport rates. This is generally true over a wide range of conditions and illustrates the need for accurate measurement or estimation of the hydraulic parameters.

6.6.3 Manning roughness coefficient

Table 6.4 shows how calculated sediment concentrations and quantities change with the assumed Manning coefficient. The table assumes a constant depth of 0.98 m and a constant sediment size of 0.4 mm.

Table 6.4 Sensitivity of computed sediment transport rates to the assumed Manning roughness coefficient

n	**0.025**	0.026	0.027	0.028	0.029	**0.030**	0.031	0.032	0.033	0.034	**0.035**
X (ppm)	**673**	616	566	520	480	**438**	410	381	354	331	**308**
Q (m^3/s)	**32.66**	31.41	30.24	29.16	28.15	**27.34**	26.33	25.51	24.74	24.02	**23.33**
Q_s (T/m)	**1.319**	1.161	1.027	0.910	0.811	**0.718**	0.648	0.583	0.525	0.477	**0.413**
% n	**-14.3**	-11.4	-8.6	-5.7	-2.9	**0.0**	+2.9	+5.7	+8.6	+11.4	**+14.3**
% X	**+53.7**	+40.	+29.2	+21.6	+9.6	**0.0**	-6.4	-13.0	-19.2	-24.4	**-29.7**

		6									
% Q	**+19.5**	+14.9	+10.6	+6.6	+3.0	**0.0**	-3.7	-6.7	-9.9	-12.2	**-14.7**
% Q_s	**+83.7**	+61.7	+43.0	+26.7	+13.0	**0.0**	-9.7	-18.8	-26.9	-33.6	**-42.5**

An error in the assumed Manning coefficient can have even more serious effects on computed transport rates than errors in the determination of depth. Percentage errors in transport rates can be five times the percentage error in the Manning coefficient. This illustrates the importance of being able to estimate the hydraulic resistance of the water course, a subject which is discussed in more detail in the manual on alluvial resistance.

6.7 Transport of Widely Graded Sediments

The bed material of upland rivers is often characterised by a wide range of particle sizes. Gravel rivers are an extreme example and, in these rivers, not only is the grading extreme but also the material is sorted with the coarse material visible on the bed and the fine material hidden beneath. Armouring of the surface is a common phenomenon.

The natural non-uniformity of river bed materials is treated in a simplified manner in both the derivation and the application of most sediment transport formulae. It is convenient to simplify the problem of sediment movement by considering uniform bed materials. Even with this assumption there can be considerable disparities amongst the various formulae (White et al.,1975).

Commonly used formulae consider an “equivalent, effective or significant” particle size, which may be D_{35}, D_{50} or another size taken from an analysis of a sample of the bed material. It is assumed that the chosen significant size will produce the correct sediment transport rate for the whole mixture when used with equations derived for uniform sediments. This is clearly a simplification because grading curves with differing shapes have different effective diameters. Furthermore, the effective size varies with the transport rate, particularly where there is a wide spectrum of sizes and where the sorting of material is pronounced.

The methods used to calculate the transport rates of widely graded sediments consider the transport rates of individual size fractions, the shielding effects where small particles hide behind larger ones and the exposure of large particles sitting on a bed of finer material. The methods are highly complex and should only be used where necessary. If the width of the grading curve, as defined by D_{84}/D_{16}, is less than 4.0 the methods given in Sections 6.1. to 6.5 which use significant size should be used.

For wider gradings, ie $D_{84}/D_{16} > 4.0$ the method given in Appendix 2 should be adopted.

6.8 Example Calculation of Sediment Transport Rates for Graded Sediments

6.8.1 Total bed material load

Example calculation:

A water course has a width of 40 m and a longitudinal slope of 0.005. The bed material comprises sands and gravels with a specific gravity of 2.65. The sizes of the sediments, in mm, as determined by a bulk sample of the material are given in Table 6.5.

Table 6.5 Sediment grading curve

D_5	D_{15}	D_{25}	D_{35}	D_{45}	D_{50}	D_{55}	D_{65}	D_{75}	D_{85}	D_{90}	D_{95}
0.40	0.75	1.5	2.1	4.5	5.5	7.0	10.0	16.0	30.0	45.0	60.0

The Manning roughness of the channel has been estimated as 0.040. Calculate the discharge and the sediment concentrations for each size fraction when the depth is 0.71 m. The temperature of the water is 15°C and the kinematic viscosity is 1.15×10^{-6} m^2/s.

Use the Manning formula to determine the mean velocity of flow, V (m/s), and equation 6.11 to determine the shear velocity, v_*. Use continuity to determine the discharge, Q (m^3/s).

$V = (1/n)\, d^{2/3}\, S^{1/2} = 1.406$ m/s

$v_* = \sqrt{(g\, d\, S)} = 0.187$ m/s

$Q = V\, b\, d = 39.9$ m^3/s

Using the Ackers and White method, an example of which is given in Section 6.3, for each size fraction and allowing for the hiding and exposure effects defined by equations 6.28 and 6.29 the results shown in Table 6.6 are obtained:-

Table 6.6 Transport rates for a graded sediment

	D (mm)	D_A (mm)	A	A_{mod}	n	m	C	F_{gr}	G_{gr}	X (ppm)	X/10 (ppm)
D_{05}	0.40	3.13	0.216	0.371	0.460	2.41	0.0209	1.238	0.1614	610	61.0
D_{15}	0.75	3.13	0.195	0.277	0.307	2.07	0.0310	0.792	0.1120	583	58.3
D_{25}	1.50	3.13	0.179	0.211	0.139	1.87	0.0326	0.499	0.0580	430	43.0
D_{35}	2.10	3.13	0.173	0.188	0.057	1.81	0.0288	0.403	0.0364	320	32.0
D_{45}	4.50	3.13	0.170	0.159	0.000	1.78	0.0250	0.287	0.0172	288	28.8
D_{55}	7.00	3.13	0.170	0.147	0.000	1.78	0.0250	0.245	0.0120	313	31.3
D_{65}	10.00	3.13	0.170	0.140	0.000	1.78	0.0250	0.216	0.0084	315	31.5
D_{75}	16.00	3.13	0.170	0.132	0.000	1.78	0.0250	0.184	0.0048	284	28.4
D_{85}	30.00	3.13	0.170	0.124	0.000	1.78	0.0250	0.150	0.0015	172	17.2
D_{95}	60.00	3.13	0.170	0.118	0.000	1.78	0.0250	0.121	0.0006	13	1.3
Total											**332**
D_{35}			0.173		0.057	1.81	0.0288	0.403	0.0480	**422**	

Sediment transport rates, Q (T/s), for each size fraction can be obtained by multiplying the factored concentrations, (X/10), given in the final column in Table 6.6, expressed as a concentration, not in ppm, by the discharge, Q = 39.9 m^3/s.

The final column in Table 6.6 gives the sediment concentrations of the individual size fractions. Sizes between D_{35} and D_{75} show similar concentrations. Sizes below D_{35} show increasing concentrations although the increase is restrained by the hiding effect (A_{mod} > A). Sizes greater than D_{75} show reducing concentrations. Here the effect of size more than compensates for the increased exposure of these particles.

The final row in Table 6.6 shows the straightforward calculation of the transport for the total bed material load based on the D_{35} sediment size and making no allowance for hiding or exposure. This method gives an answer for the total transport rate some 25% higher than the answer obtained by doing the more detailed analysis. The method gives no indication of the movement characteristics of individual size fraction. The example shows that to calculate the sediment transport rate for graded sediments the assumption of one representative sediment size may not provide results with the required accuracy.

6.9 Programs for Calculating Sediment Transport

The equations to predict sediment transport appear complicated but they can easily be inserted into a spreadsheet or simple computer program. The software DORC (Design of Regime Canals), SEDFLUX and SANDCALAC available from HR Wallingford have a number of sediment transport theories programmed into them. These computer programs are useful for doing calculations at one or a few cross-sections. They are thus a useful tool when carrying out simple desk studies. Sediment deposition or erosion depends upon the variation of sediment transport from one section to the next. To study particular problems this may require sediment transport calculations being carried out at a large number of sections for a large number of flow conditions. In these circumstances it may be easier to use a numerical river model which has a morphological component for example iSIS Sediments.

7 Application of Sediment Transport Equations to Natural Channels

7.1 Introduction

All sediment transport theories are empirically based and most of these theories are based either wholely or primarily on laboratory data. Investigations in the laboratory are very important to elucidate the mechanics of sediment transport and to develop appropriate predictive equations but care has to be taken in applying equations developed in a laboratory context to natural rivers as the characteristic conditions in laboratory channels are often different from those in natural rivers. The conditions in laboratory flumes are normally characterised by little variation in both depth and bed sediment composition across the width of the flow whereas the conditions in natural channels are often highly variable across the width. Thus in natural channels the flow depth, velocity and bed composition may vary across the width of the channel. Unlike laboratory flumes, the local bed slope in natural channels may also not be similar in magnitude or direction to the corresponding water surface slope.

7.2 Calculating Flow Conditions in Natural Channels

Sediment transport is a nonlinear function of the flow variables and, in general, is very sensitive to the assumed flow conditions. This means that great care must be taken in determining the flow parameters to be used in calculations of sediment transport. In this context it must be realised that different approximations and methods of calculation may be appropriate when considering different types of problems. Thus, for example, a method of determining the flow parameters for flood defence purposes may not be sufficiently detailed or accurate to act as a basis for sediment transport calculations. As an example of this, in calculating flow in a natural channel the assumption of normal flow is sometimes made. This is usually only an approximation as the variability along a natural channel means that normal flow is rarely attained. Though such an approximation of normal flow may be adequate to determine the flow parameters for other purposes, an assumption of normal flow is unlikely to provide sufficiently accurate estimates of flow conditions to enable accurate calculations of sediment transport to be carried out.

Thus, in calculating sediment transport, the method used to determine the flow conditions should be sufficiently accurate to ensure the required accuracy of the sediment transport predictions.

7.3 Spatial Variation of Flow Along and Across the Stream

In many natural streams the composition of the bed and the banks may vary and also the type and degree of vegetation cover. The result of this is that the hydraulic roughness of the boundary of the channel varies both across the channel and also longitudinally. Even in a channel with an approximately uniform cross-section this leads to spatial variations in the flow. Such variations in flow conditions will cause significant variations in the sediment transport rate both across the section and along the channel.

To take these variations into account requires the calculation of the lateral distribution of flow across the channel. Any such method of calculating the lateral flow distribution should be capable of simulating:

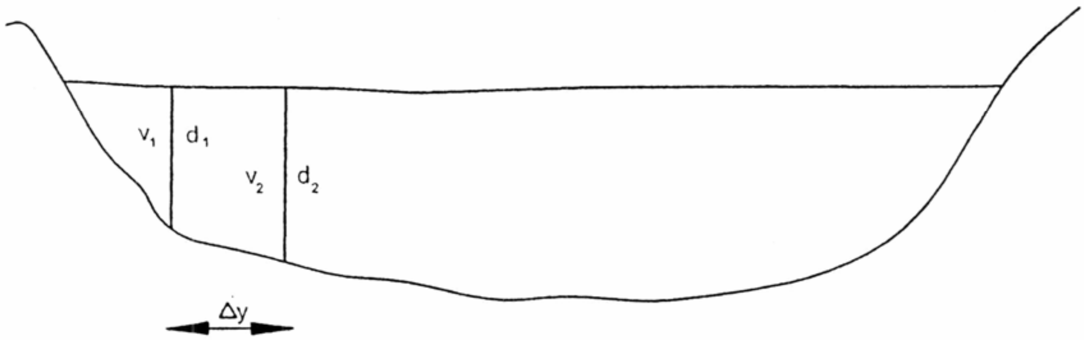
- spatially varying hydraulic roughness,
- spatially non-uniform cross-sections
- lateral shear stress developed by lateral variations in flow velocity.

Thus in non-uniform channels the accurate determination of sediment transport requires that one takes into account the effect of the lateral distribution of flow velocity and depth.

7.4 Calculating Sediment Transport within the River Channel

If the flow conditions vary across a channel then consideration has to be given to the best method for calculating the sediment transport rate. One can calculate the sediment transport rate using section-averaged values of the flow parameters but though this approach has the advantage of simplicity, the averaging that this implies may produce errors. Alternatively one can determine how the flow variables vary across the section and then evaluate the sediment transport rate at a number of verticals across the section and then sum them to give the total sediment transport rate, see Figure 7.1. This latter method, though more complex, should provide a more reliable estimate of the sediment transport rate than using the section averaged variables, see Figure 7.2.

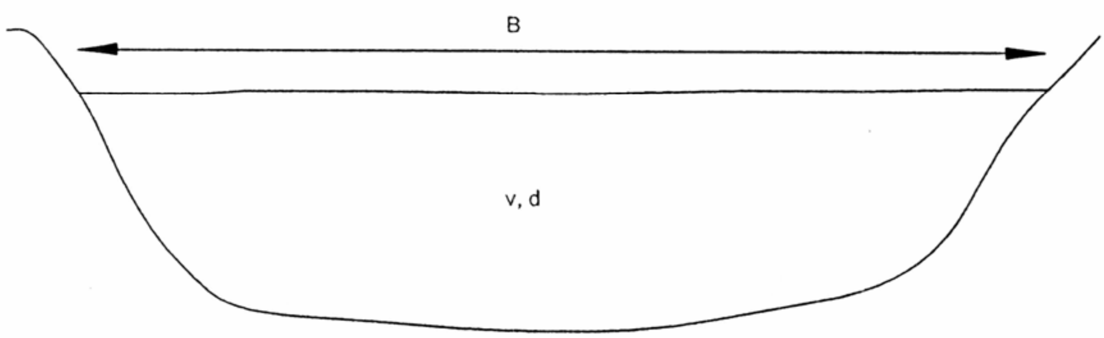
Figure 7.1 Method for calculating sediment transport on a number of verticals



Sediment concentration at a vertical $X_i = X\ (V_i,\ d_i\ ,\ S)$

Total sediment load is $\sum v_i \quad d_i\, \Delta y_i\, X$

Figure 7.2 Method of calculating sediment transport using section-averaged variables



Sediment concentration X = X (v, d, S)

Total sediment load is B v d X

Seed (1996) demonstrated that, when calculating sediment transport in a channel, the use of section averaged values of the velocity and depth could lead to errors of up to 40% in the calculated value of the sediment transport. He showed that the sediment transport rate varies across a natural river cross-section as the depth and velocity varies and that this results in a difference between the value calculated using section averaged values of the velocity and depth and the value calculated using point values of velocity and depth summed over the cross-section. This was due to the fact that sediment transport is a nonlinear function of the flow variables and so using the average values of the independent variables depth and velocity gives a different result than averaging the calculated point values of the sediment transport rate. Seed demonstrated that the difference between the two values of the total sediment transport rate was primarily related to the shape of the channel cross-section, see Figure 7.3. He provided a method whereby, for a given channel cross-section shape, the error resulting from using the section-averaged values could be estimated. This is based on the use of a shape parameter obtained by integrating the square of the local depth over the width of the width of the channel. Thus the shape factor is defined as:

$$\frac{\int h^2 dy}{WD^2}$$

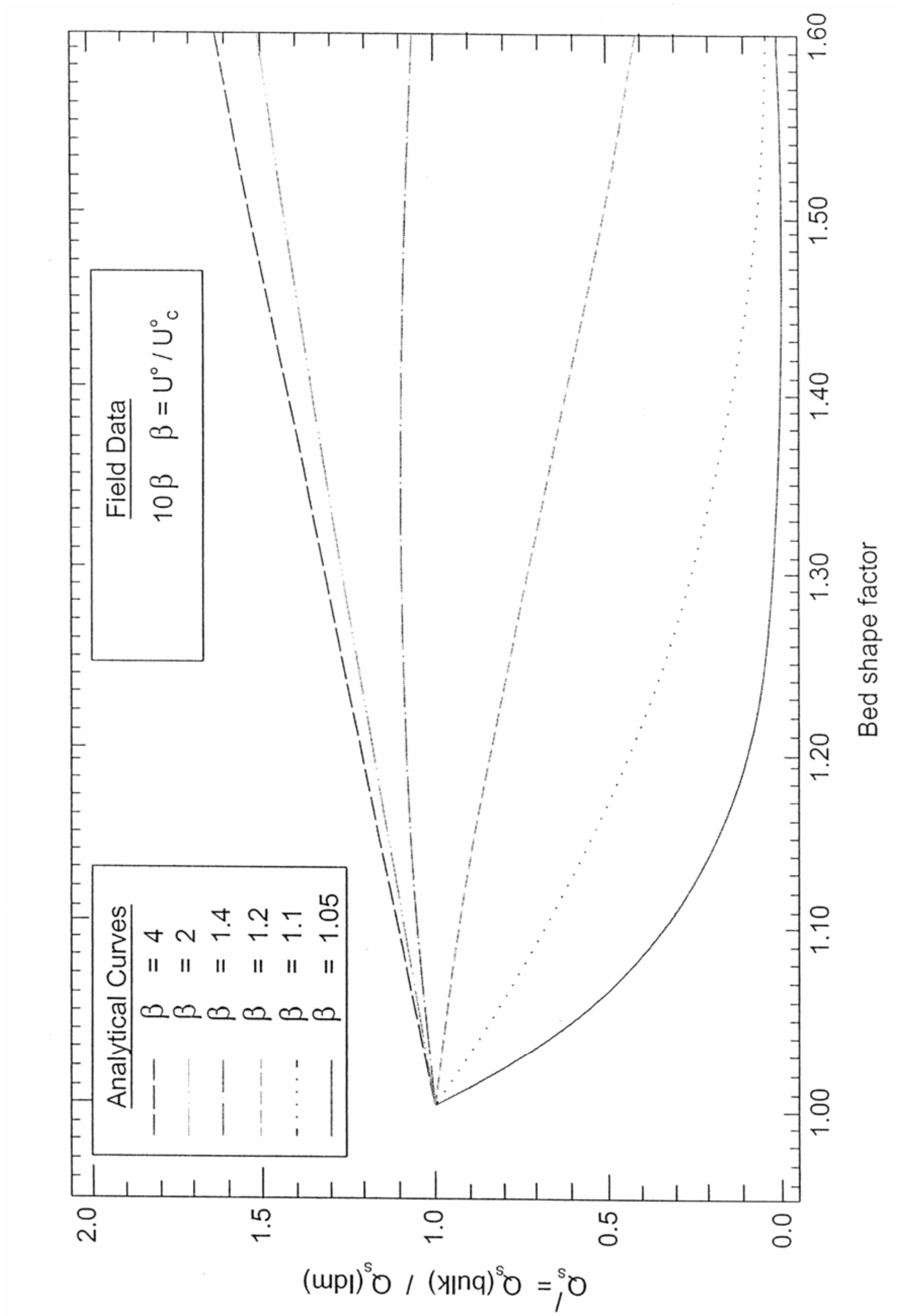
where h is the local flow depth
W is the water surface width
D is the hydraulic mean depth and
y is the distance across the cross-section of the channel.

7.5 Calculation of Sediment Transport in Channels with Floodplains

Many UK rivers have a main channel and then floodplains on one or both sides. This generates marked variations in flow depth and velocity across the channel during flood flows. This lateral variation generates similar difficulties in applying sediment transport theories to channels with overbank flows as were discussed above for inbank flows. When flow occurs on the floodplains of channels, the flow on the floodplain interacts with the flow in the main channel. Thus the flow in the main channel and hence the sediment transport is affected. The purpose of the research described in Seed (1996) was to investigate the problems of determining the sediment transport in a river channel with overbank flows. An important component in determining the sediment transport rate is to determine the flow conditions both on the floodplain and in the main channel. In an analysis of the impact of this on sediment transport, Ackers suggested that this could significantly reduce the sediment transport in the main channel. This indicates that careful consideration has to be given to the application of sediment equations to natural river channels if one is to ensure that the predictions of sediment movement are correct. If the suggestion by Ackers is correct then this would suggest that the predictions of sediment transport using section-averaged flow parameters and ignoring lateral variations and interactions between the flow in the main channel and the floodplain could be seriously in error when the flow is out of bank.

Overbank flow also introduces sediment onto the floodplain where it is deposited. This raises bank heights, which can lead to surcharging of the banks and may ultimately lead to bank failure. The deposition on the floodplain can also reduce the conveyance of the floodplain in floods. As pollutants are frequently attached to sediments, sedimentation on the floodplain can frequently lead to the storage of polluted sediments on the floodplain, which may be re-mobilised as a result of bank failure.

Figure 7.3 Sediment transport rate as a function of the channel shape parameter



7.6 Spatial Variation of Sediment Composition Along and Across the Stream

In many natural channels the composition of the bed may vary across the width of the channel, particularly in channels in which the sediment is widely graded. In channels in which the sediment is approximately uniform this problem does not arise. If the bed sediment composition does vary spatially then this leads to a number of problems. The first is related to determining the bed sediment composition. A number of samples may need to be taken across the cross-section to determine the variability of the bed sediment composition. A second problem relates to the calculation of sediment transport. It may not be sufficient to use an average bed sediment size and instead it may be necessary to take account of the variation of bed sediment size across the section. Thus the sediment transport rate should be calculated at a large number of verticals across the section using not only local values of flow velocity and depth but also local values of the sediment size. Unfortunately, there appears to be no information available on when this should be done, or the potential errors that might be incurred if such a procedure is not carried out.

7.7 Local Variations in Bed Slope

The sediment transport rate depends upon the local bed slope. A simple illustration of this is that if the local bed slope exceeds the angle of repose of the sediment then the sediment will move down slope irrespective of the flow conditions. In laboratory investigations of sediment transport it is common for the bed slope and the water surface slope to be more or less parallel so that the influence of variations in local bed slope is not apparent. In natural channels, however, it is quite possible for the local bed slope to be very different from the water surface slope. In these circumstances the affect of the local bed slope is to modify both the magnitude and direction of sediment transport. There is no general agreement on the method required to take this effect into account but the method of Kovacs and Parker (1994) is highly regarded. Thus in calculating local values of sediment transport it is necessary to include the effect of the local bed slope.

7.8 Impact of Plan form

The plan form of a channel has a major impact on the distribution of flow velocities within a channel (Sellin and Willetts, 1996). Even in a channel with a uniform cross-section, the velocity distribution at the apex of a bend tends not to be uniformly distributed but is heavily skewed to one side or the other. As sediment transport is sensitive to the flow conditions, this has a significant impact on the overall sediment transport rate. Thus the plan form of a channel can have a major impact on the amount of longitudinal sediment transport. It should be noted that calculations in which section-averaged velocities are used may not indicate the magnitude of this effect. The analysis of such plan form effects is not possible with a model that does not take account of the flow patterns induced by the plan form of the channel. This suggests that 1-D numerical models may not be appropriate to study these types of problems and that it may be necessary to use 2 or 3-D models instead.

7.9 Influence of Structures or Geological Constraints

Many mobile-bed channels flow through a significant depth of alluvium and, in these situations, the size, shape and slope of the channel are determined by the inter-action of the flow and the mobile-bed material. Occasions do arise, however, where not all the material through which the channel flows is mobile or in which parts of the alluvium are more mobile than other parts. An example of this is when a river flows over an inerodable rock outcrop. In this case the local slope of the river is constrained by the fixed sill level provided by the rock. In other situations one or more banks may also be constrained by being difficult or virtually impossible to erode. In all these cases the flow in the channel is affected and this will have an impact on the sediment transport rate. In the type of examples given above the impact is readily amenable to analysis.

7.10 Two Stage Channels

In 1991 Ackers developed a method to predict the flow in two-stage channels. This was based on dividing the flow into that on the two floodplains and that in the main channel and calculating average flow conditions for each region. To calculate the flow in each region Ackers took account of the interactions between the main channel flow and the flow on the floodplains. This interaction led to the flow on the floodplains being increased and to a reduction in the flow in the main channel.

As part of this work Ackers considered the impact that these lateral interactions would have on sediment transport. By applying his method of flow calculation he demonstrated that the sediment transport rate in the main channel should reduce significantly when flow in a channel went out of bank. Subsequent experimental work, some in the Flood Channel Facility at HR, has indicated that for straight channels there is little or no such reduction in sediment transport rate. It is instructive to consider the reasons that might explain why the observed impact of floodplain flow on sediment transport is less than that suggested by the analysis of Ackers.

The Ackers analysis determines an average flow velocity in the main channel and how this is reduced by the interaction with the floodplains. The analysis is one-dimensional and so is unable to consider the distribution of these changes in velocity distribution. In his analysis the interaction reduces the average flow velocity in the main channel and as sediment transport is sensitive to flow velocity this significantly reduces the sediment transport rate. Subsequent experimental work, supported by analysis using methods such as the lateral distribution method, indicate that the impact of the interactions with the floodplains on the flow velocities is confined to the edges of the main channel. This means that for wide channels a major part of the flow and hence sediment transport is unaffected by the interaction. This means that, though the average flow velocity is reduced, the impact on sediment transport is modest.

The analysis of sediment transport in meandering channels with floodplains is more complicated than that for straight channels and is a topic of active research..

There is a general lesson to be learnt from this which also has application to 2 and 3 dimensional modelling. A method for flow calculation that is perfectly adequate to determine the flow conditions may not provide sufficiently detailed and accurate information to adequately determine sediment transport. Thus it is possible to have a one-dimensional model that adequately predicts flow velocity and water depth but which does not provide an accurate representation of sediment transport. In two and three-dimensional models it is possible to reproduce the flow conditions adequately in terms of flow velocities and depth but the representation of the shear stress may not be sufficient to provide an adequate description of sediment movement.

8 Prediction of Alluvial Resistance

8.1 Introduction

This chapter deals with the prediction of alluvial resistance. It follows the descriptions given in Chapter 3 dealing first, and briefly, with the traditional methods of assessing channel resistance in fixed-bed channels using the Manning (1895) and Colebrook and White (1937,1939) formulations. There then follows a general description of those methods that assess the alluvial resistance as affected by sediment movement and the associated development of bed forms of various types. The detailed equations, calculation procedures and examples are given in the Appendix 4.

8.2 Fixed-bed Channel Resistance

Traditional methods for the prediction of the channel resistance are useful for determining the capacity of natural channels or the depth at a particular flow. There is an abundance of evidence that enables the roughness coefficients to be related to field conditions. Qualitative allowances can be made for the nature of the channel and other factors such as seasonal variations in vegetation. They are not able, however, to consider the variations in bed roughness as influenced by sediment transport. Thus changes in roughness with changing discharge due to the development of bed features are beyond the scope of traditional methods.

8.2.1 The Manning (1895) approach

Manning developed an equation which, with the passage of time, has been shown to be reliable and relatively robust in the range of conditions to which it is applicable.

Formula

$V = (1/n)\, R^{2/3}\, S^{1/2}$, (8.1)

where
- n is the Manning roughness coefficient ($s/m^{1/3}$)
- R is the hydraulic mean radius (m)
- S is the energy gradient
- V is the mean velocity (m/s)

$R = A / P$, (8.2)

where
- A is the cross-sectional area of the channel (m^2)
- P is the wetted perimeter of the channel (m)

8.2.2 The Colebrook and White (1937, 1939) approach

Nikuradse (1933) studied turbulence in smooth pipes and his work was extended by Colebrook and White (1937, 1939) to include artificially roughened pipes. They further developed a theoretical framework which covered both smooth and roughened boundaries and which defines a transition between the two extremes of smooth and rough turbulent flow conditions.

Formulae

The general expression is:-

$$V = - 4 (2 g R S)^{½} \log_{10} [k_s / 14.8 R + \nu / (3.187 R (2 g R S)^{½})] \qquad (8.3)$$

where g is the acceleration due to gravity (m/s^2)
k_s is the effective roughness height
ν is the kinematic viscosity (m^2/s)

Where flow conditions are in the smooth turbulent range, that is, where the friction factor is a function of the Reynolds number, equation 8.3 simplifies to:-

$$V = 4 (2 g R S)^{½} \log_{10} [3.187 R (2 g R S)^{½} / \nu]. \qquad (8.4)$$

Where rough turbulent conditions apply, that is, for high Reynolds number flows where the friction factor depends upon the relative roughness, equation 8.3 simplifies to:-

$$V = 4 (2 g R S)^{½} \log_{10} [14.8 R / k_s]. \qquad (8.5)$$

8.3 Alluvial Resistance

8.3.1 Introduction

This section describes methods of predicting the alluvial resistance of channels as affected by the movement of bed sediments. These methods apply to conditions where the bed may exhibit ripples, dunes and other types of bed form. They do not, however, define explicitly what bed forms are present. Instead, they predict resistance based on the physics of sediment movement in terms of sediment and flow properties.

There is a wide range of theories available to predict alluvial resistance. In general we would recommend the use of the White, Paris and Bettess or White, Bettess and Wang equations. In a number of tests by independent authors these equations have produced good agreement with observations over a wide range of conditions.

All the methods for predicting alluvial resistance discussed are steady state methods in which the resistance is dependent upon the local values of the variables involved. They also assume that the friction does not depend upon the history of previous flows, only upon the flows prevalent at the time. Where there is active sediment movement the methods describe changes in resistance with changes in flows although if flows change rapidly there will be some error due to a lag between the flow and the corresponding bed form. Where the transport rate is zero, it is clear that the resistance will be influenced by bed forms that were created by earlier, higher flows and under these circumstances the methods fall down. This is not a serious limitation because the main application of the alluvial resistance methods is in the determination of channel capacity or flow depths at high flows, under which conditions sediment transport will usually be significant.

8.3.2 Slope separation techniques

From physical principles it can be argued that the overall resistance of the bed of a channel depends on both the “grain” resistance and the “form” resistance. The fundamental assumption in the so called slope separation technique is that these two types of resistance are independent and additive:-

$$\tau = \tau' + \tau'' \qquad (8.6)$$

where τ' is the bed shear stress associated with grain roughness (N/m^2)

τ'' is the bed shear stress associated with form roughness (N/m^2)

In the slope separation approach, the energy losses due to grain roughness and form roughness are associated with fractions of the slope S as the slope S is related to the energy loss. An alternative approach is to associate the energy losses due to grain roughness and form roughness with proportions of the depth or hydraulic mean radius. Thus the hydraulic mean radius is split in the same way as the shear stress, such that:-

$$R = R' + R'' \text{ and} \qquad (8.7)$$

$$\tau' / R' = \tau'' / R'' \qquad (8.8)$$

where R' is the hydraulic mean radius associated with grain roughness (m)

R'' is the hydraulic mean radius associated with form roughness (m).

The most common methods to use the slope separation technique are Einstein and Barbarossa (1952) and Engelund (1966, 1967). Both methods involve the use of empirically derived functional relationships. Both methods require iterative calculations to gain values which satisfy both equations 8.7 and 8.8 and also the various functional relationships which determine τ', τ'', R' and R''. Neither method has been shown to be of general application and both methods lack at least one relevant parameter, based on physical reasoning and dimensional analysis. They are described briefly below.

Einstein and Barbarossa (1952):

Einstein and Barbarossa derived an empirical relationship between V / v_*'' and ψ'.

where v_*'' is the shear velocity associated with the form roughness (m/s)

ψ' is the dimensionless grain shear as defined by Einstein and Barbarossa

The empirical relationship was derived from data for a number of rivers in the Missouri River basin and is shown in Figure 8.1. Also shown in the figure is some of the data gathered by White, Paris and Bettess (1979). These data show a great deal of scatter suggesting that there may be a missing parameter in the Einstein Barbarossa approach. To quantify the grain roughness effects they assumed a Manning-Strickler form of relationship using a shear velocity based on R' rather than R.

Engelund (1966, 1967):

Engelund developed an approach that related the dimensionless grain shear to the dimensionless total shear as shown in Figure 8.2. Their work was mainly concerned with dunes and was based on a scaling argument that implied that all flows over a dune bed are similar.

Figure 8.2 shows the plot of θ against θ'.

where θ is the dimensionless total bed shear as defined by Engelund (1966)

θ' is the dimensionless grain shear as defined by Engelund (1966)

The empirical expression, together with some of the data assembled by White, Paris and Bettess is shown in Figure 8.2. Some scatter is apparent but less than that indicated for the Einstein and Barbarossa approach. However the data for differing grain sizes plots at differing locations suggesting that the approach has a missing parameter, possibly particle size.

Figure 8.1 Slope separation after Einstein and Barbarossa (1952)

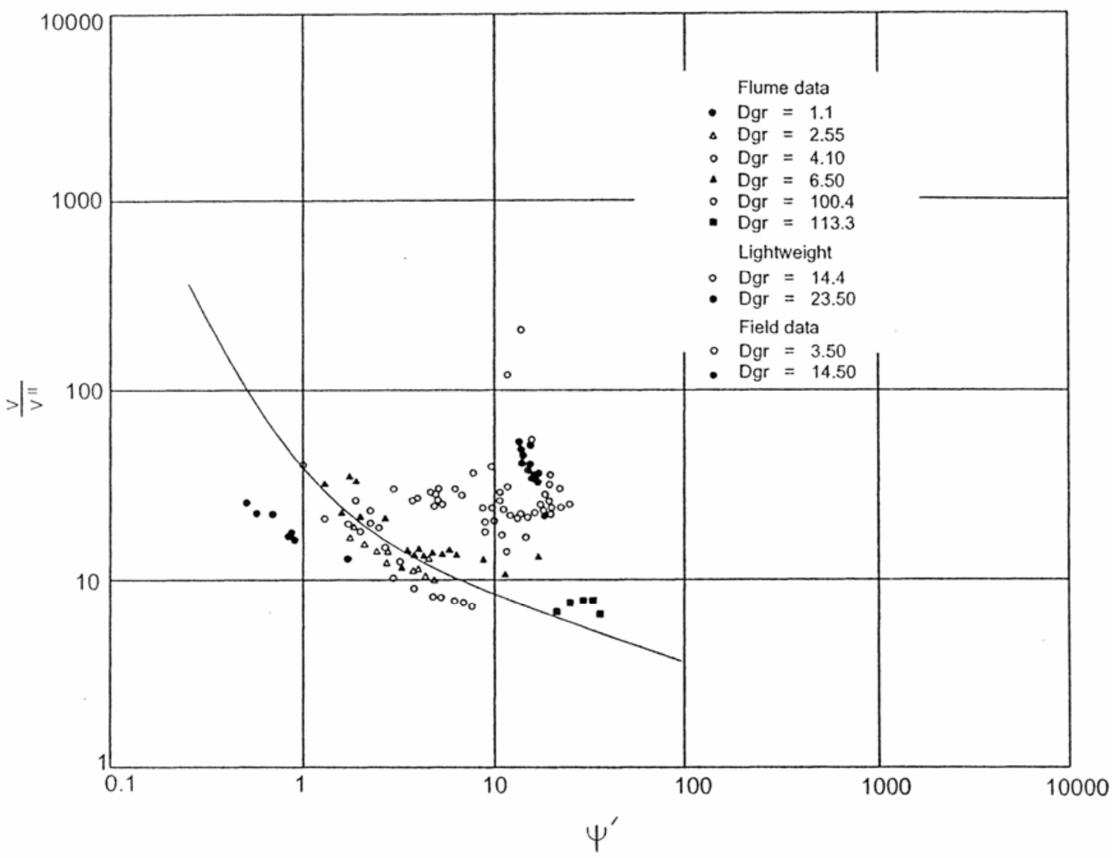
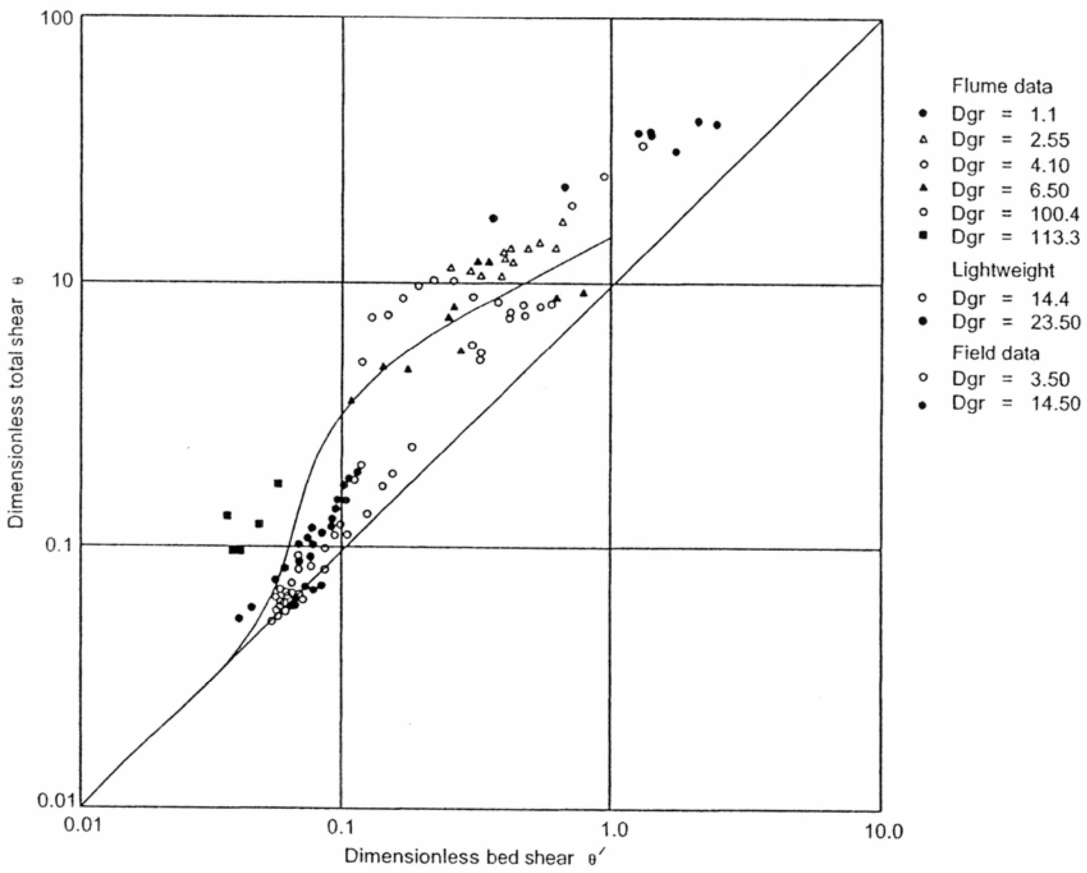


Figure 8.2 Slope separation after Engelund and Hansen (1966, 1967)



8.3.3 General approach to alluvial resistance

Ackers and White (1973) and Ackers (1993) put forward a theory for predicting total bed material load in channels. The theory assumed that the quantity of fine, non-cohesive bed sediments travelling mainly in suspension correlated with total boundary shear stresses and that the quantity of coarse, non-cohesive bed sediments travelling mainly as bed load correlated with grain shear stresses. Sediment size was defined in terms of the non-dimensional parameter, D_{gr} :-

$$D_{gr} = D \left[g (s - 1) / \nu^2 \right]^{1/3} \qquad (8.9)$$

where D is the representative sediment diameter (m)

s is the specific gravity of the sediment

The data suggested that fine sediments were in the range $D_{gr} \sim 1$, that is, sand sizes less than 0.04mm. Coarse sediments were in the range $D_{gr} > 60$ ie sediment sizes in excess of approximately 2.5mm. Intermediate sizes were termed “transitional” and the relative influences of total and grain shear were established in terms of D_{gr}.

D is selected to be a representative sediment diameter. Depending upon the particular application different sediment diameters may be selected. For uniform sediments White, Paris and Bettess recommended the use of the D_{35} value in their equations but recommended using the D_{65} value if widely graded sediments were present.

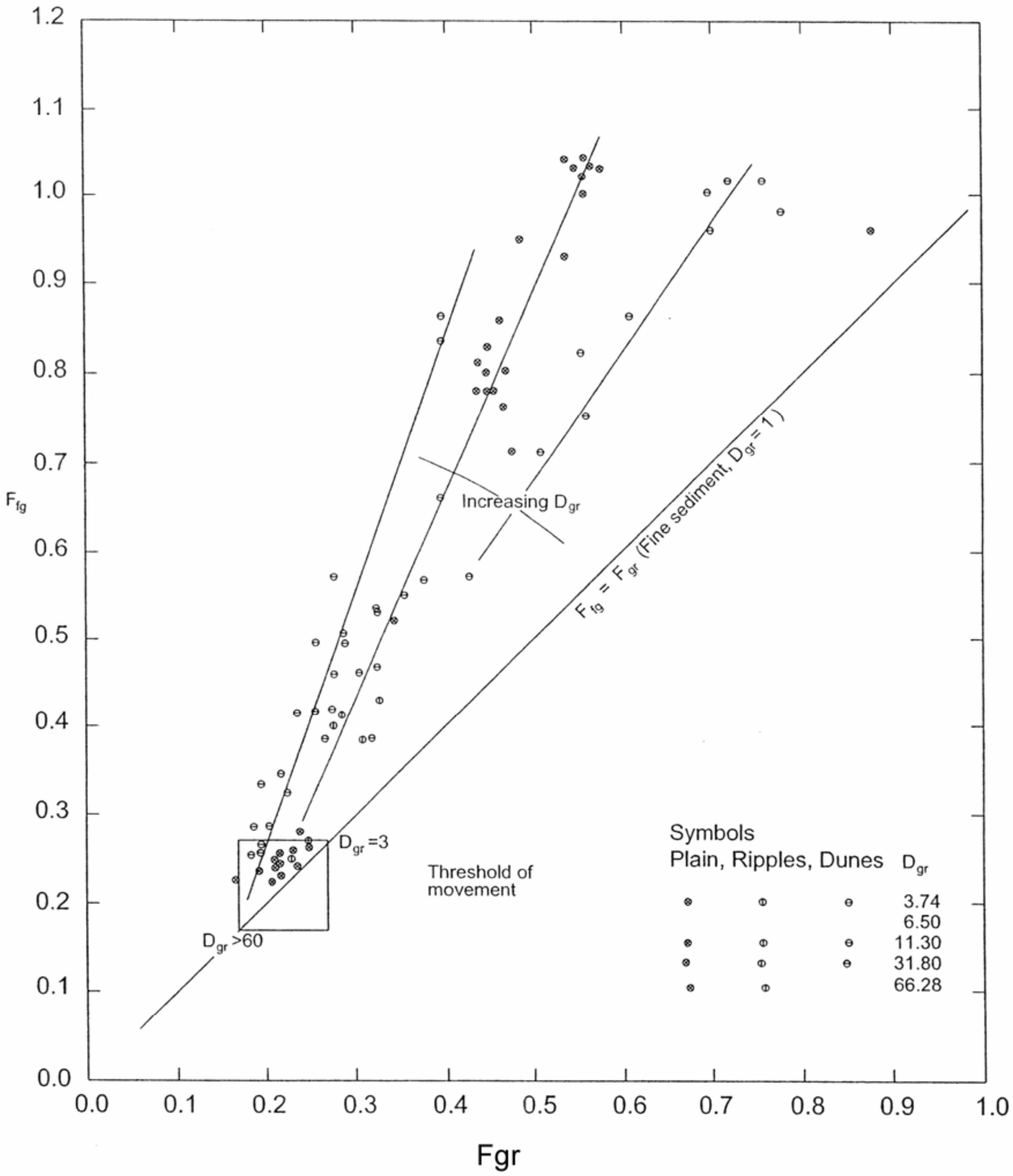
Sediment movement is predicted in terms of a sediment mobility number based on the ratio of shear stresses to immersed weight of the sediment particles. The form of the mobility number was set up such that only the relevant shear forces were used, ie total shear for fine sediments, grain shear for coarse sediments and an intermediate value for transitional sediments depending upon D_{gr}.

White, Paris and Bettess (1979):

White, Paris and Bettess (1979) built on the ideas presented earlier by Engelund (1966) and showed that the missing parameter in the Engelund approach was particle size. White, Paris and Bettess were able to show that alluvial resistance could be defined in terms of F_{gr}, F_{fg} and D_{gr}, see Figure 8.3.

White, Paris and Bettess produced two functional relationships, one for near uniform sediments based on the D_{35} size and one for graded sediments based on the D_{65} size.

Figure 8.3 General approach to alluvial resistance after White, Paris and Bettess (1979)



The White, Paris and Bettess equations are valid for the lower flow regime ie where ripples and/or dunes occur on the bed. This condition occurs when the non-dimensional unit stream power, U_E, is less than 0.011, see Equation A3.1. A detailed description of the method is given in Appendix 4.

White, Bettess and Wang (1987):

White, Bettess and Wang (1987) further developed the methodology to include the upper flow regime. In this case data for graded sediments was not available in the quantities required and the development was restricted to near uniform sediments.

The White, Bettess and Wang equations represent conditions for near uniform sediments in the lower and upper regimes. These equations for upper regime bed forms give very different answers for the frictional resistance of alluvial channels to those for lower regime bed forms because they apply to very different bed forms. Hence, in predicting alluvial resistance, it is necessary to develop a methodology for determining which regime is applicable in particular circumstances. A further requirement is to be able to determine under what circumstances the transition will take place from one regime to the other.

The authors proposed criteria, based on assessments of the non-dimensional unit stream power, to determine whether the bed forms were upper or lower regime.

The authors further suggested that, as flows increase, conditions remain in the lower regime until the value of U_E^L reaches 0.011. Subsequently, as flows decreases, conditions remain in the upper regime until U_E^U falls to 0.011. The question of hysteresis effects during flood events remains to be solved satisfactorily.

We would recommend the use of the White, Paris and Bettess method or the White, Bettess and Wang method as appropriate to determine alluvial friction. A detailed description of the method is given in Appendix 4.

8.4 Example Calculations

Example calculations are given in Appendix 4. Here the results of the application of Manning's equation, the Colebrook White equation and the White, Bettess and Wang equations to the same example are discussed as they throw light on the way that these methods work.

Table 8.1 Comparison of computed discharges

	Discharges (m^3/s) at the following depths (m)				
	0.5	**1.0**	**1.5**	**2.0**	**2.5**
Manning	15.41	47.89	92.22	146.0	207.8
Colebrook and White	13.63	45.34	89.60	143.8	206.3
White, Bettess and Wang	14.55	40.08	73.17	168.9	222.84

The results are also shown in Figure 8.4. The White, Bettess and Wang (1987) approach suggests that transition from the lower to the upper regime occurs between the depths of 1.5 m and 2.0 m, see Table A4.3. Interpolation suggests that the transition occurs at a depth of approximately 1.84 m. The implication is that as the depth increases from 0.5 m to 1.5 m the bed features increase in size from ripples through to dunes. Plain bed conditions occur in the range 1.5 m to 2.0 m and antidunes start to be formed in the range of depths between 2.0 m and 2.5 m. The flows indicated by the White, Bettess and Wang (1987) method, as compared with the other two methods, show the appropriate trends. The other methods over-predict flows in the range 1.0<depth (m)<1.5 because they do not anticipate the development of dunes. They also under-predict flows in the range 2.0<depth (m)<2.5 when the bed features are washed out and the bed becomes relatively smooth. This comparison indicates how a fixed-bed method will not properly simulate the changes in hydraulic roughness which arise from changes in alluvial resistance.

8.4.1 Programs for applying roughness predictors

The equations for alluvial resistance presented above appear complicated but they can easily be inserted in a spreadsheet. The software DORC (Design of Regime Canals) available from HR Wallingford has a number of alluvial roughness predictors included within it, including the White, Paris and Bettess equations for uniform sediments in lower regime, Engelund's equations and Einstein and Barbarossa's equations. Manning's equation is also included in the software. DORC does not include the ability to predict alluvial resistance for upper regime conditions.

Figure 8.4 Comparison of computed discharges

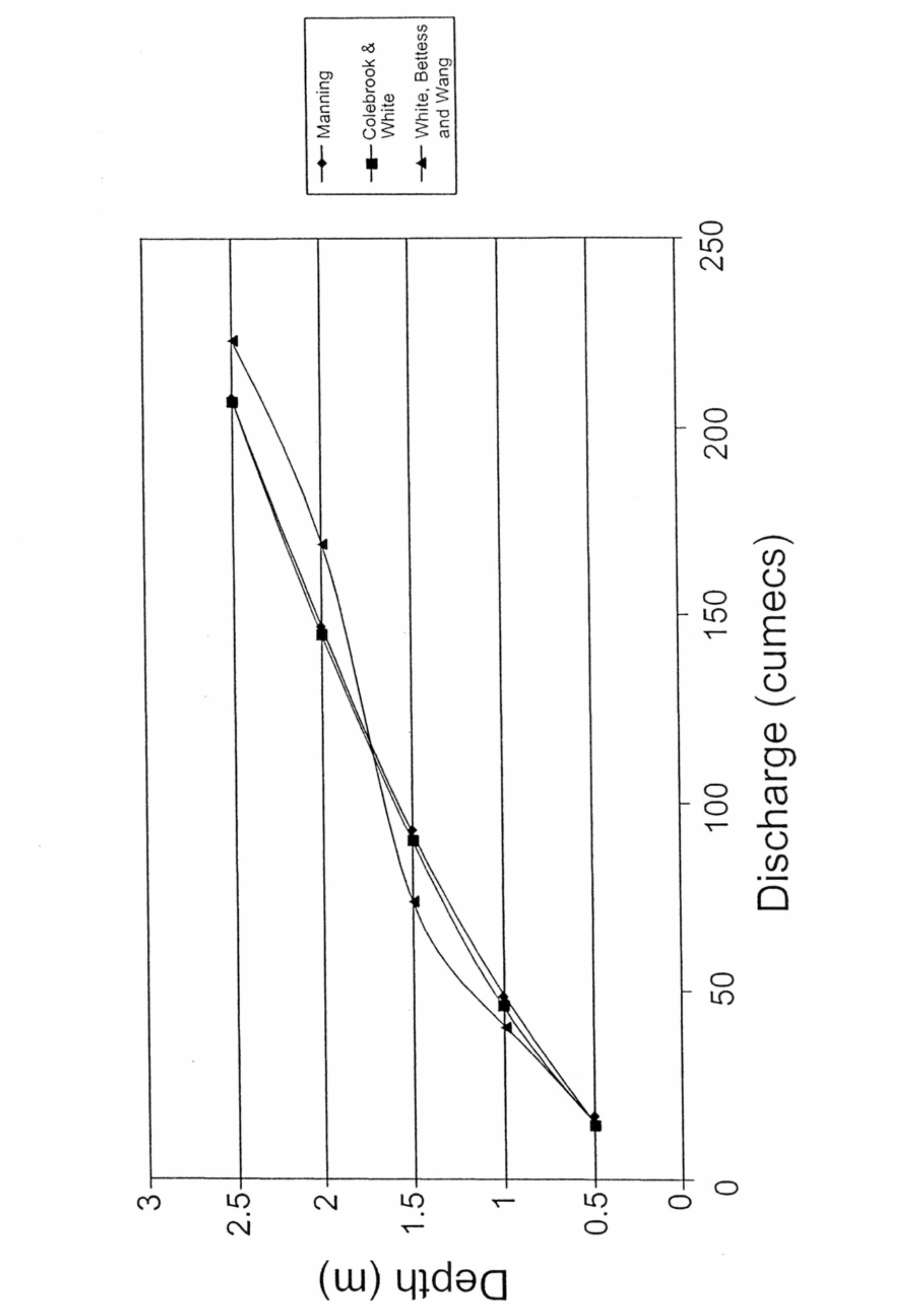
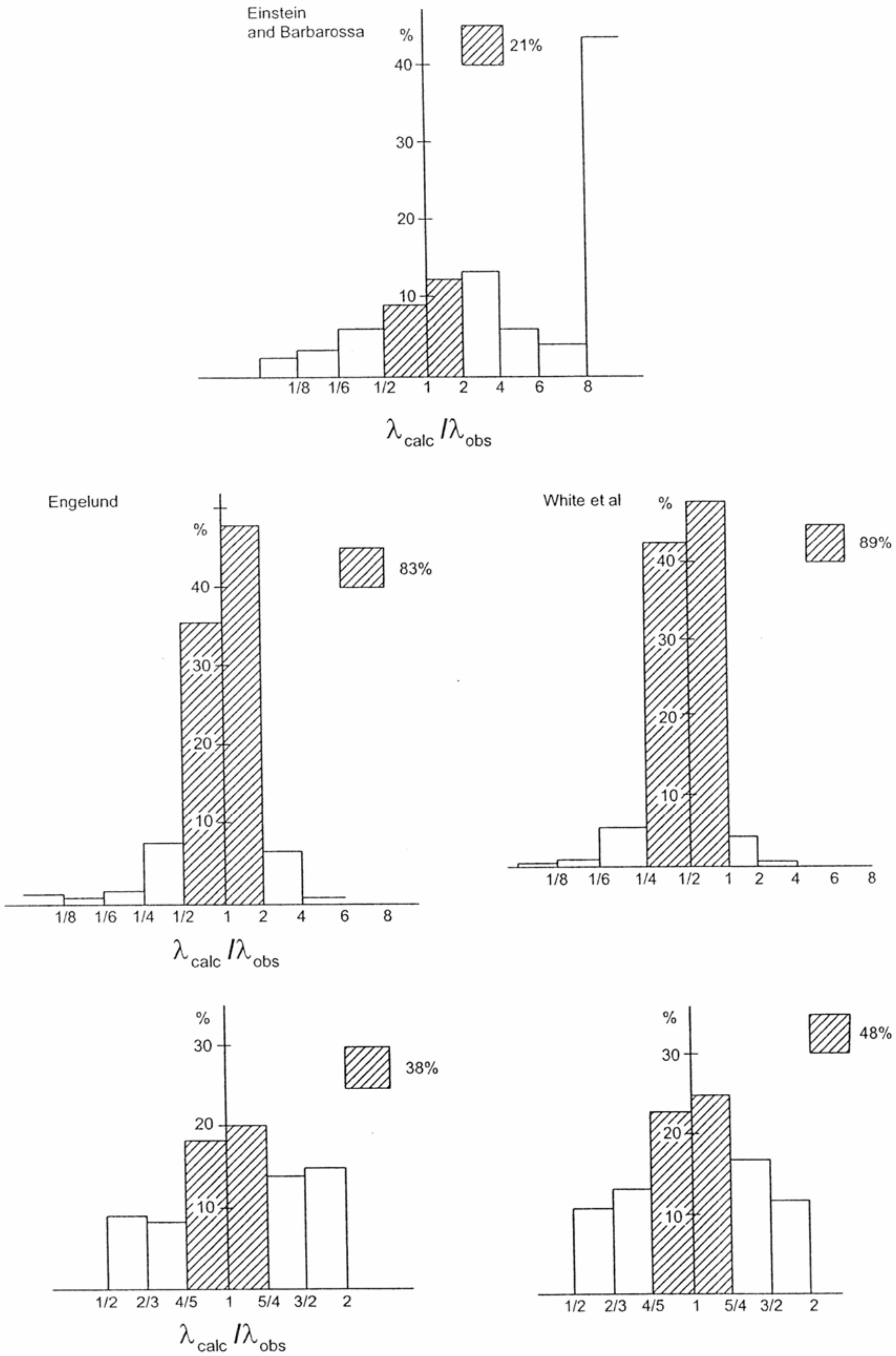


Figure 8.5 Discrepancy ratios for theories of alluvial resistance



8.4.2 Accuracy of predictions of alluvial resistance

White, Paris and Bettess carried out a comparison of the methods proposed by Einstein and Barbarossa, Engelund, Raudkivi and White et al. The comparison was made on an extensive data set covering a wide range of conditions. Figure 8.5 shows the discrepancy ratios for the friction factor, that is, the ratio of predicted to observed values. Thus perfect agreement is represented by a discrepancy ratio of 1. This information is summarised in the following table:

Theory	%of discrepancy ratios within factor of 2	%of discrepancy ratios between 0.8 and 1.25
White et al	89	48
Engelund	83	38
Raudkivi	73	25
Einstein and Barbarossa	21	n/a

It can be seen that on the data used the White et al method had a similar but slightly better accuracy than the Engelund method. The Raudkivi method was less successful and the Einstein and Barbarossa method was poor at predicting alluvial resistance.

8.4.3 Comparison of predictions of different methods

It is instructive to compare the predictions of the different methods for a particular example. The following conditions were assumed:

Q = 35 cumecs

S = 0.005

B = 10 m

D_{16} = 1.95 mm

D_{35} = 2 mm

D_{50} = 2.05 mm

D_{65} = 2.1 mm

D_{84} = 2.15 mm

D_{90} = 2.2 mm

For the purposes of the calculation it has been assumed that the channel has a side-slope of 1:1.5. The predictions of the various theories are as follows:

	Mannings n	d (m)	V (m/s)
White et al	0.034	0.468	1.233
Engelund	0.0330 .	0.458	1.260
Brownlie	0.030 .	0.428	1.348
Van Rijn	0.017	0.303	1.909

It is evident that the predictions of the theories of White et al, Engelund and Brownlie give broadly similar results but that of van Rijn is significantly different.

8.5 Alluvial Resistance in Gravel Rivers

8.5.1 Introduction

Alluvial resistance in rivers arises from both grain roughness and form roughness due to the presence of bed features. In many sand bed channels the grain roughness is small due to the small size of the individual sediment particles whereas the form roughness is large due to the large size of bed features such as ripples or dunes. In many gravel rivers, however, bed features such as dunes are small or absent but the grain roughness is large due to the size of the individual sediment particles. Thus in these gravel rivers the hydraulic roughness is often dominated by the grain roughness and form roughness is of less importance. In this section we will discuss methods to predict the hydraulic roughness of gravel rivers.

8.5.2 Range of validity

The division between sand and gravels on which this Chapter is based is somewhat arbitrary. What is observed is a continuum of behaviour in which, as the sediment size increases, the relative importance of form and grain roughness alters. To impose an arbitrary limit on the validity of the equations that are described here it is suggested that they are applicable to sediments with a D_{84} size larger than 20 mm.

8.5.3 Alluvial resistance for gravel bed rivers

A large number of studies have been carried out investigating the roughness of gravel bed rivers, see for example, Bathurst (1985), Bray (1979, Hey (1979 and Limerinos (1970). Though superficially the equations that have been derived are very diverse in appearance, it can be seen in Appendix 5 that all the equations are closely related to the Colebrook-White equation with the assumption that the roughness length, k_s, is replaced by 3 D_{84}. It is recommended, therefore, that for gravel rivers the Colebrook-White equation is used. Solutions of the Colebrook-White equation have been tabulated in Tables for the Design of Pipes, Sewers and Channels by HR Wallingford and Barr. To use the equations based on pipe diameter for open channel calculations one can use the equivalence between diameter and hydraulic radius of D = 4 R.

The applicability of the Colebrook-White equation to gravel rivers with $k_s = 3\ D_{84}$ suggests that in gravel rivers the resistance is dominated by skin roughness. The skin roughness itself is dominated by the size of the larger sediment sizes present and hence the dependence on the D_{84} size. This is consistent with the observation that bed features are normally low or absent in gravel rivers.

8.5.4 Small depth/diameter ratios

As the ratio of depth to sediment diameter reduces ($d/D_{84} < 5$) the nature of the flow and the turbulence structure becomes modified. In these situations it is not clear what is the appropriate form of equation to use. Bathurst collected data for slopes between 0.4 and 4% and for $d/D_{84}<10$. On the basis of this he proposed an equation of the form:

$$\left[\frac{8}{f}\right]^{\frac{1}{2}} = 5.62\log\left[\frac{d}{D_{84}}\right] + 4 \qquad (8.10)$$

Because of its semi-logarithmic nature the equation represents the overall trend of the data envelope (for a range of sites) but is less representative of the at-a-site variation for individual sites. Thus the equation tends to underestimate the resistance coefficient f at low flows and overestimate it at high flows .

It can be shown that the Bathurst equation (eq 8.10) is, in effect, the Colebrook White equation with $k_s = 3\ D_{84}$, see Appendix 5. Thus the equation has a much wider range of applicability than that suggested by the author. In the light of the similarity between the Bathurst equation and the Colebrook White equation, it is recommended that when $d/D_{84} < 5$ the Colebrook White equation is also used with $k_s = 3\ D_{84}$. Users should be aware, however, that the impact of the small depth-diameter ratios means that the accuracy of the predictions may be reduced.

For channels in which the sediment size is comparable with the depth of flow, the definition of section properties becomes very difficult. An estimation of the depth is difficult as it varies widely from place to place and the origin from which it should be measured is not well-defined. In such situations the prediction of alluvial resistance can be subject to significant errors. Fortunately for those involved in the prediction of floods, the uncertainty reduces as the value of the relative flow depth (d/D_{84}) increases.

8.5.5 Pool-riffle sequences

Many gravel bed rivers exhibit pool-riffle sequences. In such cases the flow conditions at the pools and riffles are very different in low flows. The riffles are characterised by shallow, fast flow while the pools have deep, slow flow. In each separate flow condition standard hydraulic equations can be used to predict the flow conditions in either pool or riffle. Unfortunately in most engineering applications the length scale over which calculations are to be made exceed the length of a pool or riffle. In this situation any length scale under consideration will contain a number of pool-riffle sequences. In this situation there are no valid methods to predict the flow. Presumably, were such a method available, it would predict some form of average of the conditions at the pool and riffle.

As the discharge increases the differences between the conditions in the pool and riffles reduce. In extreme conditions the water surface slope becomes more uniform. In these conditions the source of the hydraulic roughness is likely to be both from the surface roughness and also from the form roughness associated with the pool-riffle sequences. It is likely that in most applications for high flows the surface roughness will predominate.

The implications of the above discussion are:
a) the prediction of flow in pool-riffle sequences is difficult
b) for low flows each type of flow should be considered separately
c) for high flows predictions may be made of the basis of surface roughness dominated flow using, for example, Hey's equation

8.5.6 Step-pool sequences

Steep headwater stream channels are often characterised by alternating steps and pools. Steps can be observed on slopes as low as 1% but fully developed step pool sequences only seem to appear on slopes on excess of 3%. At low discharges the water flows over or through the boulders forming each step and plunges into the pool below. At high flows the steps may be drowned out and their form concealed by the flow. Field data suggests that the flow resistance may change substantially between low and high flows. A 100-fold reduction in flow resistance has been reported between low and high flows. At present there is no recommended method for predicting the flow in such conditions.

8.6 Flowchart for Calculating Alluvial Resistance

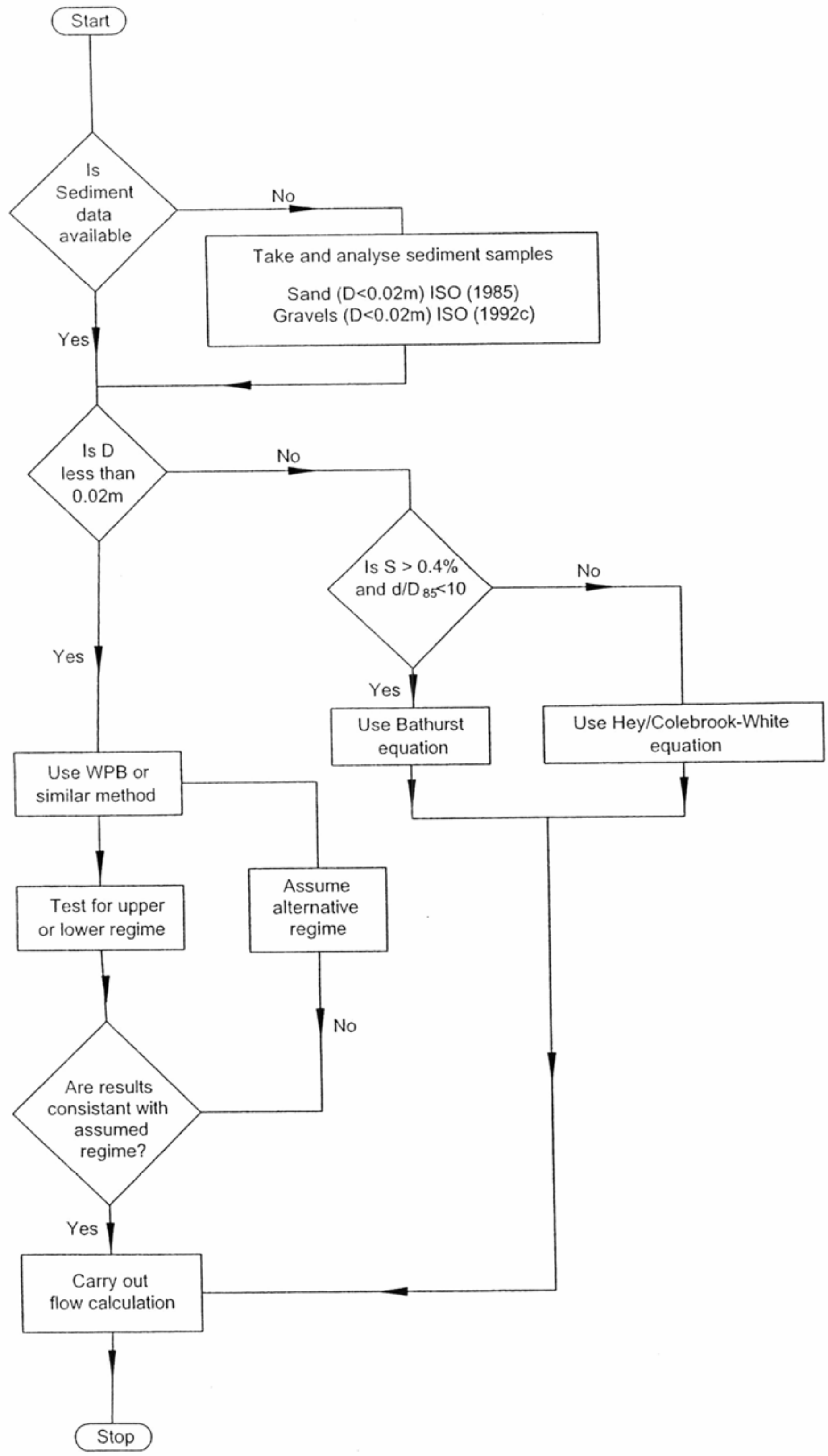
Figure 8.6 gives a flow chart for determining alluvial resistance. It is intended to clarify the selection of the appropriate theory to apply in particular circumstances. The details of the methods mentioned are to be found in Appendix 4.

8.7 Implications for River Engineers

8.7.1 Design

In alluvial channels the hydraulic roughness may vary as the flow conditions change. Any design has to take this change in roughness into account. This implies the need to measure or calculate the hydraulic roughness and determine its value over the anticipated range of flow conditions. These values then have to be used with the appropriate discharges to determine the design flow conditions.

Figure 8.6 Flow chart for determining alluvial resistance



Greater reliance should always be placed on measurements of hydraulic roughness from the site than on theoretic predictions. In the absence of such measurements from site, theoretical predictions of hydraulic roughness have to be used.

The procedure that should be adopted for design depends upon the imposed design conditions. It may be that the designer has only to consider extreme flood conditions. In situations in which sediment transport is significant then a range of flow conditions will need to be considered from the critical discharge (that is the smallest discharge at which sediment motion takes place) upwards. If environmental issues are raised then it may be necessary to consider normal and low flows. A theory of alluvial resistance can be used to assess the hydraulic roughness for each band of discharges. The number of different discharge bands that need to be considered will depend upon the sensitivity of the hydraulic roughness to discharge. At least initially it is suggested that the calculations are carried out for three discharges which should include the largest flow being considered. On the basis of these results it will be possible to determine whether a larger number of flows need to be considered.

If the variation in hydraulic roughness between different flows is small then one hydraulic roughness can be adopted for all flow calculations. If the hydraulic roughness varies significantly then different values of hydraulic roughness will have to be adopted for each range of discharges. It may well be that in many cases the alluvial resistance will increase as the flow increases. For the purposes of determining flood capacity then the value of hydraulic resistance determined for the design flow should be used. In some cases, however, it may be that for the largest flows the alluvial resistance is lower than for smaller flows. This case will require some judgement by the engineer. It is suggested that in these cases to determine flood capacity the largest calculated roughness value is used, even though this is not the roughness value associated with the largest flow. This will allow for the time required for bed forms to adjust to varying flow conditions and will also introduce a factor of safety. If there is evidence that the smaller hydraulic roughness will always be achieved during the design flow conditions then the designer may decide to select the lower hydraulic roughness. If calculations are not being carried out to determine flood capacity but for other reasons such as the calculation of sediment transport then the engineer must use his judgement as to the appropriate hydraulic roughness value to use.

It is recommended that to calculate alluvial resistance in sand bed channels the White, Paris and Bettess equations described above are used initially. A check should be carried out to determine if the bed forms are in the lower or upper regimes. If they are in the upper regime then the equations by White, Bettess and Wang should be used. For gravel bed channels the Colebrook White equation can be used with a suitable value for k_s. If the bed is plane then k_s can be approximated by $3D_{84}$; if there are bed features, bends or other sources of friction then the effect of these can be included by increasing the value of k_s up to approximately $4.5D_{84}$.

In some channels the alluvial resistance may be the major source of roughness and no other sources of roughness will need to be considered. Such channels will normally consist of wide channels with a bed of mobile sediment whose banks either do not provide a significant source of roughness or whose contribution to the overall roughness of the channel is small. In other channels there may be other significant sources of hydraulic roughness. In these channels the hydraulic roughnesses of the different surfaces must be assessed and then combined to give an overall hydraulic roughness for the channel. For methods of combining the hydraulic roughness of different surfaces see Appendix 7 which is derived from HR Wallingford and Barr (1998).

It must be remembered that the bed features respond to local flow conditions and thus even at a constant discharge variations in flow conditions from one location to another may generate spatial variations in bed features and hence hydraulic roughness. Such variations may occur from one cross-section to another or they may also occur across a single cross-section. Where the flow is spatially non-uniform this should be taken into account and investigated appropriately. If the nature of the flow varies from one cross-section to another then the alluvial resistance calculations should be carried out for each section or each group of similar sections. The case of variations across a single cross-section is discussed in the Section 7.9.

If the height of bed forms is significant in comparison with the flow depth then the bed forms may affect the water levels and the conveyance of the channel. In this context it is suggested that if the height of the bed forms exceeds 10% of the flow depth under consideration then special attention is paid to the potential impact on conveyance. In these situations, locally the water surface slope will vary over the bed form. The steepest slope will be expected near the crest of the bed form and the flattest slope near the trough. In considering the overall conveyance of a reach such variations can be averaged out but it is probably advisable to take a bed level corresponding to the average of the crest and trough levels.

8.7.2 Example calculations

The following example is given to illustrate how the White et al method might be used in design. The following quantities have been assumed:

Width of channel	10 m
Slope	0.005
D_{35}	2.0 mm
T	15^0 C

A side-slope of 1:1.5 has been used in the calculation. It is assumed that there is no information available from site on observed roughness values during flood conditions.

Using the White et al method the roughness of the channel was estimated for a range of discharges

Q (m^3/s)	5	15	25	35
Mannings n	0.032	0.035	0.036	0.037

It can be seen that the alluvial resistance increases with discharge for the range of values considered here. If the design for flood protection is 35 m^3/s then any calculation of flood levels at this flow should use a Mannings n value of 0.037. If water levels are required for smaller discharges, perhaps for the design of environmental works, then the Mannings n value appropriate to that discharge should be used in the calculations.

In the above example the Mannings n value was a monotonic function of the discharge but this does not always occur.

If we assume the following:

Channel width	10 m
Slope	0.005
D_{35}	0.08 mm

then we have the following

Q (m^3/s)	20	40	60	80
Mannings n	0.015	0.016	0.016	0.015

If the design discharge for flood levels is 80 m^3/s then the question arises is what is the appropriate Mannings n value to use in the water level calculations. In view of the possible delay in the bed features adjusting to the flow conditions during a flood we would recommend the use of the n value of 0.016 rather that the value of 0.015 associated with the design discharge. This advice would be dependent upon the size of variation in the n value and the likely rate of change of discharge with time. Any reduction in alluvial resistance with increasing discharge is normally associated with a reduction in bed form size as one approaches upper regime conditions. It is necessary therefore to check whether conditions are in the lower or upper regime, see Appendix 4.

When considering carrying out channel works there are a number of potential sediment effects that should be considered. The impact of alluvial resistance may be that flood levels are then too high and flood embankments may need to be considered. Such embankments, by modifying the flow conditions, will lead to alterations in the alluvial resistance that must be taken into account. The alteration to the flow caused by flood embankments may also modify the sediment transport in the channel. This can lead to sediment deposition and bed level rise, thus negating the impact of the embankments or resulting in long-term maintenance commitments.

8.7.3 Alluvial resistance and numerical models

Very few numerical models have alluvial resistance predictors built into the model itself. This means that the user has to carry out the calculations of alluvial resistance separately from the model and insert the appropriate values of hydraulic roughness into the model. In this situation it is difficult to incorporate the variability of the hydraulic roughness with discharge that is commonly associated with alluvial resistance. In this situation the user must determine the alluvial resistance associated with the discharge of greatest interest and use that value of hydraulic roughness in the knowledge that this value of hydraulic roughness will not be appropriate for other discharges.

8.7.4 Impact of development of bars on flow conveyance

The cross-sections of natural channels are rarely uniform and it is common to find the depth of flow varying significantly across the channel. It is widely known that at bends the deep flow occurs on the outside of the bend while the flow is shallow on the inside. This configuration is due to a shoal or bar developing on the inside of the bend. The development of such shoals or bars at bends is common. It is to be expected that such bars will have an effect on the overall conveyance of the channel. Laboratory based studies in the Flood Channel Facility at Wallingford (Ervine et al, 1993) have indicated that the presence of bars can reduce the non-friction losses in the channel and hence lead to increases in conveyance. Thus a channel with a naturally developed bed form will have a higher conveyance than a channel with a regular cross-section of similar area. At the moment there is not sufficient information to determine the optimum bed configuration. Such a configuration is likely to depend upon the particular flow conditions and will vary as the flow varies. Indeed if the sediment on the bed of the river is mobile then whatever initial geometry is adopted there is no guarantee that it will be maintained under all flows.

The impact of alluvial resistance on the overall conveyance of a channel and floodplain depends upon the depth of water on the floodplain. The impact of a reduction in the alluvial resistance and hence increase in the conveyance of the main channel depends upon the amount of overbank flow and reduces as the depth of flow on the floodplain increases. For large depths of flow on the floodplain the flow on the floodplain itself may dominate the flow in the main channel. In this case the significance of the main channel geometry reduces.

This poses a number of problems for the designer. Whatever initial channel geometry is adopted, if the bed material is mobile, it is likely to be modified through time depending upon the sequence of flows experienced by the channel. If a uniform section is assumed for design conditions then upon completion of the works it is likely that the bed configuration will modify which will affect the conveyance. At bends it would appear that the development of point bars may lead to an increase in the conveyance of the channel.

The designer may want to account for this improvement in conveyance in the design calculations. To do this a number of problems must be addressed. With the present state of knowledge we can neither predict the bed configuration that will minimise the energy losses and hence maximise the conveyance, nor can we predict the bed configuration that will result from a given flow sequence.

Studies on alternate bars suggest that the development of alternate bars is not accompanied by an overall increase in the total resistance to the flow. Laboratory experiments have indicated that as alternate bars develop the resistance associated with the alternate bars increases but at the same time the resistance due to accompanying smaller features, such as ripples, reduces leading to the overall maintenance of the total resistance.

In a number of schemes, particularly restoration schemes, it is necessary to import foreign bed material. This raises a number of issues. If the restoration scheme modifies the flow conditions, it may well result in changes to the alluvial roughness. Even if the flow conditions are unchanged, if the bed material size is altered by the importation of foreign sediments then this too may lead to changes in the alluvial roughness.

8.8 Maintenance

Maintenance is normally carried out to preserve the conveyance of a river channel. In discussing the issue of maintenance we must distinguish between two possible situations. In one there is net long-term aggradation of sediment within the river channel, with or without the development of bed features. In the other there is no net long-term aggradation but bed features develop which locally modify water depths.

In the first case in which there is net aggradation, if no sediment is removed from the river then there will be a progressive reduction in the conveyance of the river channel and a corresponding increase in flood levels. In this situation flood levels can only be maintained by periodic removal of sediment. The rate of sedimentation is related to bed levels. As the bed levels rise the rate of sedimentation will reduce and ultimately will cease. Investigations should be carried out to determine whether the long-term equilibrium bed levels would be acceptable.

In the second case, even if there is no net aggradation bed features may develop which locally reduce flow depths. The conveyance of the channel can be affected by the presence of such bed features and by appearing to reduce the flow area, the expectation is that bed features will reduce the conveyance. Thus, the removal of bed features may appear superficially to be attractive. Removing such features should both reduce the hydraulic roughness by reducing the form losses and increase the conveyance by lowering the average bed level. Indeed removing significant bed features should give an immediate increase in conveyance. Unfortunately bed features are created in response to the prevailing flow conditions and if the flow conditions remain unchanged then it is likely that the bed features will reform. The only exceptions to this will be if the bed features are only formed during unusual flow conditions or if the upstream sediment supply has been removed. Even the latter situation will not necessarily prevent the reformation of dunes. In all other cases it is likely that the bed features will reform again in the future. If the sediment transport rates are low or zero then reformation may be slow but in all other cases bed features are likely to reform rapidly. In these situations removal of features may not be a sensible long-term maintenance strategy and it is suggested that other methods are explored to maintain the channel conveyance.

Unfortunately the other methods that immediately spring to mind may also have significant sediment effects. One option is to reduce or remove the amount of sediment available in the river reach by reducing the sediment supply. This can be done by controlling the sediment supply at source or by collecting sediment upstream at designated areas, that is, use sediment traps. Unless there is an existing aggradation problem in the reach, this is likely to cause degradation of the river bed downstream. By reducing the incoming sediment load there are also likely to be changes in the bed sediment composition which will have an impact on the environment. Another method would be to accept the hydraulic roughness and water levels associated with the bed features and to construct flood embankments to provide the required flood protection. Unfortunately, as described above, this may well affect sediment transport in the channel and hence lead to bed level rise.

The most sustainable option is to accept the natural processes in the river system and the associated hydraulic roughness. If this is not a viable option then it is not possible to give general advice about the best option to pursue. Any maintenance strategy is specific to the particular circumstances of the river. As described below, it is possible to use modelling to investigate the range of options available.

In developing a maintenance strategy it is important to consider the geomorphological context of the problem. If the geomorphic cause of the problem can be identified then this can guide the selection of a suitable mitigation strategy (Sear, Newson and Brookes, 1995)

Little work appears to be available on the speed of formation of bed features. It seems likely that the speed of formation is related to the local sediment transport rate and the size of features. If the sediment transport rate is low then bed features will be slow to develop. If the excess shear stress is larger and the sediment transport rate is higher then bed features are likely to develop more quickly. As was described in Section 2.5, dunes develop in the laboratory in periods measured in hours and in major river systems in periods of a few days.

During maintenance it may seem to attractive to remove shoals or bars developed at bends to increase the channel conveyance. As described above, on the basis of experiments carried out in the Flood Channel Facility, Ervine et al (1993) concluded that the presence of such point bars could increase the overall channel conveyance. If the existing bed of a river is disturbed to make the channel more uniform but with no overall removal of sediment then it is likely that the overall conveyance of the river will be reduced. Fortunately, perhaps, the impact of such work is likely to be short lived as the next significant flow is likely to reform the bars. To effect an increase in conveyance it would be necessary to remove sediment. If only a small quantity of sediment is removed then the benefit of the increased cross-sectional area may not be sufficient to overcome the reduction in conveyance caused by the modified channel shape.

Work by Jaeggi (1984) suggests that the development of alternate bars within a channel does not increase the overall hydraulic roughness. If this is indeed the case then the removal of alternate bars may not provide a reduction in hydraulic roughness and so may not provide an increase in conveyance.

Before doing any work to modify the sediment bed of a river the likely consequences should be considered. If the bed of the river is armoured then removal of the surface layer will expose the finer sediments below. This can lead to enhanced bed erosion and the release of fine sediment into the flow. The work is also likely to have a significant impact on the size of sediment on the bed of the river. This will have an impact on the local plant and animal communities. The release of fine sediment can have a harmful effect on plant and animal communities downstream. In particular it may influence the survival of fish spawn. To reduce the risk of such adverse impact on fish communities, the time of year when any work is carried out should be carefully selected.

Even if fine sediment is not released, any disturbance to the existing bed is likely to have an effect on the local eco-system. Under these circumstances it is suggested that the advice of an ecologist is sought before planning and carrying out the work.

Under certain circumstances it appears that large single bed features may develop. Two examples are described. In a large sand bed river in Bangladesh (River Meghna) there was a large ‘island’, which was approximately 1,000 m long, 60 m wide and 20 m high. An analysis of historic maps suggested that the feature was moving downstream at a rate of between 5 and 20 m a year. In many ways this ‘island’ could be classes as a sand dune, or perhaps a ‘mega-dune’. The cause of the formation of such a feature is not clear. The feature appears to move as a result of sediment being eroded from the upstream toe of the dune and then sediment being deposited in the downstream lee. The removal of sediment from the upstream toe may permanently reduce the size of the feature. It would seem likely, however, that removal of sediment from the downstream portion of the feature would just slow its downstream progress. If the dune were to be completely removed it is not clear whether or not it would reform.

In the second example, a large bed feature was observed in a steep gravel bed river. It was approximately 60 m long with a shallow upstream face but a steep downstream face, approximately at the angle of repose of the bed material. The maximum height was approximately 1.5 m. It appeared to have formed during a major flood and was downstream of an area of significant morphological activity. It seems likely that the sediment in the feature was derived from upstream bed and bank erosion. In this case, were the feature to be removed it would be unlikely to reform before the next major flood event.

Numerical river models can be used to predict flood levels in a river reach. Such models can be used to assess the impact on flood levels of changes to the hydraulic roughness, bed level or channel shape. Thus modelling can be used to inform decisions about maintenance strategies.

8.9 Application to Rivers

8.9.1 Introduction

The first flow equations, such as those due to Chezy or Colebrook-White, were based on flow in pipes which have a regular geometry. The methods for calculating alluvial resistance, such as Engelund or White Paris and Bettess, are based on laboratory data. In laboratory flumes the bed level and flow conditions are normally uniform across the width of the flume. In natural rivers the conditions are rarely uniform across the channel width. This means that in natural channels the flow conditions, and hence bed features, may vary across the channel. The problem then arises as how to use methods for estimating alluvial resistance to calculate the flow velocity or conveyance of a cross-section. The application of hydraulic equations to irregularly shaped, natural river channels or channels with floodplains has generated a number of problems that are discussed below

An important aspect governing the methods to be used is the accuracy that is required, which itself depends on the use to which the results are to be put. Some approaches may be perfectly satisfactory to provide approximate estimates of flow conditions during feasibility calculations, other methods may be satisfactory for the design of flood schemes, while the accurate assessment of sediment movement during a flood may need even more detailed flow calculations.

In the past the most common application for hydraulic equations was to estimate water levels for given discharges, particularly flood discharges and have also been used to provide flow velocity and depth values to enable sediment transport calculations to be performed. More recently it has been realised that to calculate the sediment transport in a natural channel it is not sufficient to use section-averaged values of the depth and flow velocity but that the flow has to be calculated at a number of verticals to determine the variation across the cross-section. The sediment transport rate at a number of verticals is then determined and the values integrated to give the total sediment transport rate. In order to do this detailed information is required of the flow velocities across a cross-section so that there may be different levels of accuracy of prediction may be required for different applications. Some methods may give acceptable predictions of the overall stage discharge relationship but may not give acceptable estimates of the distribution of flow velocities across the section. Thus such methods are acceptable for the estimation of, say, flood levels, but would not be acceptable for the estimation of sediment transport rates.

8.9.2 Estimation of in-bank flows

For in-bank flows one difficulty that arises is where different parts of the perimeter of the channel have different roughnesses. The first approaches to this problem were to divide the channel into different sections each with a homogeneous roughness and to apply the hydraulic equations to each sub-division in turn. Although this approach has been widely used, unfortunately it has a number of shortcomings. Equations such as Manning's equation or the Colebrook-White equation are non-linear and cannot be evaluated by adding up sub-components. Nor is it obvious that these types of equation are applicable to just part of a channel cross-section. When Manning's equation or the Colebrook-White equation are applied to a complete section there are two types of boundary: either an interface with a solid boundary of the channel or the interface with the air. When a channel is divided into sections then there are three types of boundary: an interface with the solid boundary of the channel, an interface with the air and a water-water interface with the sections on each side. By the nature of the flow there is normally a shear stress across this water-water interface. This shear stress is, in general, very different from that applied to a solid boundary or the interface with the air. In these circumstances it seems highly likely that the original flow equations are not applicable to each sub-division separately and this is confirmed by much laboratory and field measurements.

8.9.3 Out of bank flows

When considering out of bank flows the problems of lateral variations in hydraulic roughness become even more extreme. It is quite common for the hydraulic roughness of floodplains of rivers to be substantially different from the roughness of the main channel. Flow in the main channel is dominated by the roughness of the main channel while flow on the floodplains is dominated by the roughness of the floodplains. Experiments have shown that there can be a substantial shear stress in the zone dividing the main channel and the floodplain. This can act to slow down the flow in the main channel and speed up the flow on the floodplain. The implication of this is that the classic divided channel methods cannot be used for out of bank cases.

Careful experiments were carried out on flow in two-stage channels in the UK Flood Channel Facility (FCF). On the basis of this data Ackers produced a method predict the flow in two-stage channels (Ackers 1992 and Wark, James and Ackers, 1994). This is based on dividing up the channel horizontally into a series of different zones, depending upon the interactions between the main channel flow and the floodplains.

As the Ackers' method relies upon horizontal divisions it follows that the main channel is represented by a sequence of horizontal divisions and that lateral variations within the main channel cannot be accounted for. If only the section-average flow characteristics are required then this is not a disadvantage. In reality, however, the interaction of the main flow and the floodplains has its strongest effect near to the edges of the main channel and has a smaller impact in the centre of the main channel. If one is only interested in section-averaged values then this is of no concern. If one wants to calculate the sediment transport rate in the section then it may be very important to take account of the lateral variation in velocity.

8.9.4 Lateral distribution methods

To overcome the disadvantages of the simple desk methods discussed above, methods were developed to take account of the lateral variation in velocity. These are called Lateral Distribution Methods (LDM) and they have been developed and verified against data obtained from the UK FCF (Shiono and Knight, 1990 and Wark et al, 1990). These methods are based on a differential equation that describes the variation in velocity or flow across a cross-section as a result of variations in both depth and roughness. A brief introduction to the principles of such a method is given in Appendix 6.

In natural channels the variation in channel shape results in lateral variations in both flow velocity and depth. As we have seen, the bed form developed, and hence hydraulic roughness, vary with both velocity and depth. Thus in natural channels there can be different sizes and types of bed forms at different points across the width of a channel. The use of point-wise methods, such as the LDM, allows the point-wise determination of flow conditions and hence the point-wise determination of bed conditions. It also allows the integration of all these effects across the cross-section and it allows the calculation of point-wise velocities across the cross-section.

8.9.5 Application of theories of alluvial resistance to rivers

As explained above, the variation in depth across a natural cross-section leads to variations in flow conditions in terms of both depth and flow velocity. These variations in flow conditions will, in turn, lead to variations in alluvial roughness across the cross-section. In many cases where the cross-section shows significant variation, it is likely that significant variations in bed features and hydraulic roughness across the cross-section will result. Thus where there are significant variations in geometry across the cross-section, one should not regard the theories of alluvial resistance as giving an overall roughness value but rather the theory will give point values of hydraulic roughness.

This can be illustrated by an example. Assume that we have a channel with a longitudinal slope of 0.0001 and sediment size of 0.5 mm. The depth across the channel varies from 0.95 m to 2.37m. Applying the White et al alluvial resistance equations at a number of verticals one can calculate the variation in hydraulic roughness across the section.

d (m)	0.95	1.28	1.59	1.87	2.12	2.37
V (m/s)	0.51	0.56	0.59	0.62	0.66	0.68
Mannings n	0.018	0.020	0.022	0.023	0.024	0.024

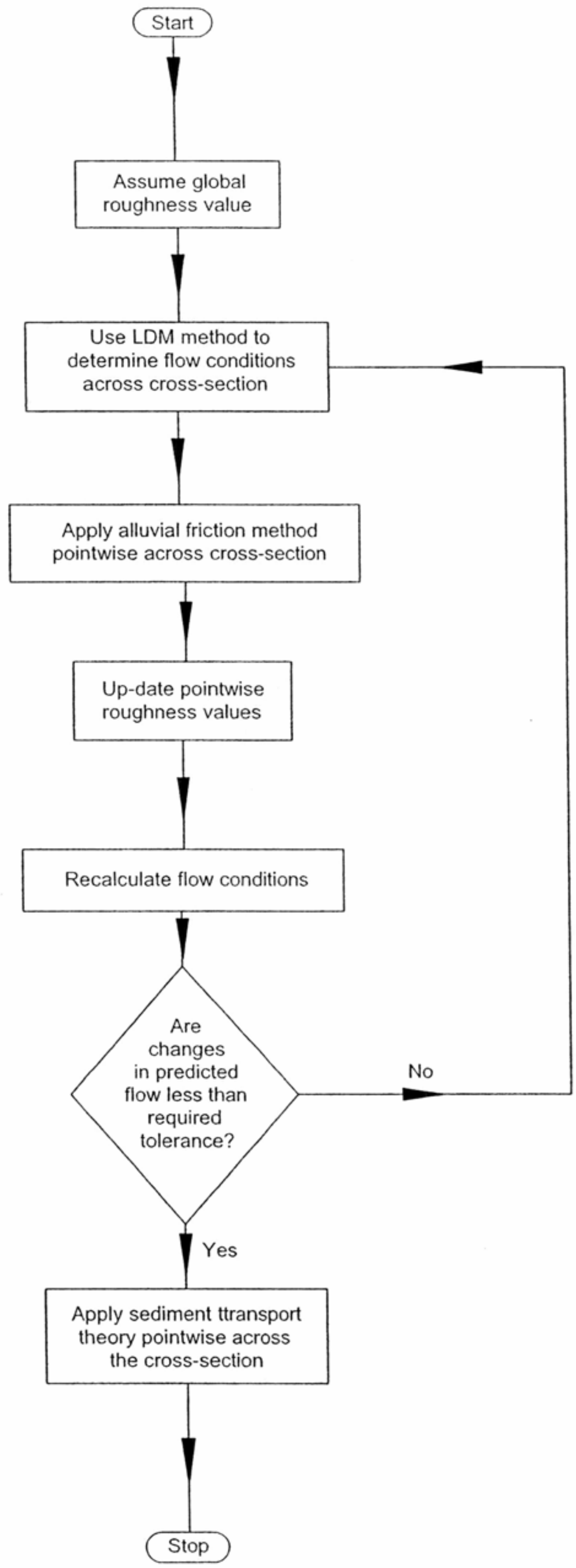
It should be emphasised that this is looking at the variation of Mannings n with depth resulting from a variation in depth across a cross-section for a single constant discharge. As can be seen the calculations indicate that the alluvial resistance will vary significantly across the section. In the above calculation a single sediment size was used. In some rivers the sediment size may vary across the cross-section, which adds further complexity.

To determine the overall hydraulic roughness for a cross-section one can use a theory of alluvial resistance to evaluate the hydraulic roughness on a number of verticals.

Once one has determined the hydraulic roughness at a number of verticals it is then necessary to sum their effect to give the total hydraulic roughness. It is likely that in any practical scheme these two calculations will have to be combined into an iterative process. Let us assume that one has an estimate for the discharge and water level. These, together with the channel cross-section, can then be used to determine the local depth at each vertical. The local depth, together with the water surface slope, can be used in a theory of alluvial resistance to determine the local value of hydraulic roughness and flow velocity. These values of depth and hydraulic roughness can then be used in a Lateral Distribution Method such as Shiono and Knight (1990) or Wark et al (1990) to determine the velocity distribution across the channel. In general this will be different to the initial estimate of the velocity distribution. On the basis of this revised velocity distribution a new estimate of alluvial resistance must be made and the process repeated until the differences between successive steps are acceptably small. A flow chart outlining this procedure is given in Figure 8.7.

Such a method has to be computer based and at the moment there is no software available to carry out such calculations. It is recommended that such software is developed.

Figure 8.7 Flow chart for determining alluvial resistance taking account of lateral variations



9 River Morphology and Fluvial Processes

9.1 Natural Channel Shapes and Slopes

9.1.1 Regime theory

It is a matter of common observation that channels with large discharges are normally wider and deeper than channels with small discharges. Similarly, larger channels normally have larger width to depth ratios than smaller channels. These observations are particular cases of the general observation that for alluvial channels there is an interrelationship between discharge, sediment discharge, sediment size, channel width, depth, flow velocity and plan form.

The first developments in this field came under the name of regime theory and were made by engineers working on the design of irrigation canals in the Indian subcontinent in the late 19th and early 20th century. They developed empirical correlations between variables describing the size and shape of alluvial channels and the theories normally take the form of three equations for the stable width, depth and slope of a channel in terms of the discharge and sediment properties.

Lacey derived the following set of empirical equations:

$$P = 2.67\ Q^{0.5}$$
$$V = 1.17Q^{0.5}f^{0.5}$$
$$S = f^{5/3}/(1750Q^{1/6}),$$

where f is the Lacey silt factor which can be derived from the sediment size using the equation:

$$f = 8D^{0.5},$$

where D is the sediment size in inches and all other units are imperial (foot – seconds) (Henderson 1966).

These equations can be transformed into metric units and, with some additions they take the form:

$$P = 4.75\ Q^{0.5}$$
$$A = 2.28Q^{5/6}/f^{1/3}$$
$$R = 0.47Q^{1/3}/f^{1/3}$$
$$V = 0.439Q^{1/6}/f^{1/3}$$
$$S = 0.000315f^{5/3}/Q^{1/6},$$

where f is the Lacey silt factor which can be derived from the sediment size using the equation:

$$f = 1.76D^{0.5},$$

where D is the sediment size in mm (Garde and Ranga Raju, 1985).

The empirically-derived regime equations indicate that the size and shape of a stable channel is determined primarily by the discharge. Other factors, such as, the presence of vegetation and bed and bank composition may also affect channel geometry but in most situations these are essentially secondary effects.

Example calculations

a) Calculate the regime channel dimensions if the discharge is 1,000 m^3/s and the sediment size is 1 mm.

If D = 1mm then f = 1.76. Applying the above equations we obtain:

P = 150 m
A = 597 m^2
R = 3.89 m
V = 1.15 m/s and
S = 0.00024.

b) Calculate the regime channel dimensions if the discharge is 20 m^3/s and the sediment size is 0.2 mm.

If D = 0.2mm then f = 0.787. Applying the above equations we obtain:

P = 21.2 m
A = 30 m^2
R = 1.38 m
V = 0.78 m/s and
S = 0.00016.

9.1.2 Analytic regime theory

The original regime theories were entirely empirical in origin. Within the last 20 years efforts have been made to develop regime theories based on fundamental equations of sediment transport and alluvial friction. It is hoped that such theories would increase our understanding of the processes leading to stable channel formation and to provide predictions of channel size and shape which are more accurate and have wider applicability. A number of such analytic regime theories have been developed. All involve a sediment transport theory and a theory for alluvial friction but the appropriate equation to use to determine channel width is less clear. A number of authors have used extremal hypotheses in which the width is adjusted until some functional is either maximised or minimised. White et al (1982) showed that a number of different extremal hypotheses lead to the same result in terms of the regime size of the channel. By comparing the predictions of the analytic regime theory with observed channel size and shapes White et al (1981a) showed that such theories can provide accurate predictions.

White et al (1981b) used rational regime theory to produce a set of tables giving the size and shape of regime channels for a wide range of discharges, sediment sizes and sediment loads.

For the examples considered above the regime tables of White et al provide the following results.

Example (a) The Tables include the effects of sediment concentration and so for a discharge of 1,000m^3/s and a sediment size of 1 mm they provide a range of predictions.

	10 ppm	50 ppm	100 ppm	200 ppm
Width	153.6 m	205 m	246 m	317 m
Depth	6.87 m	4.20 m	3.18 m	2.27 m
Velocity	0.95 m/s	1.16 m/s	1.28 m/s	1.39 m/s
Slope	0.00006	0.00025	0.00049	0.00096

Example (b) The Tables include the effects of sediment concentration and so for a discharge of 20m^3/s and a sediment size of 0.2 mm they provide a range of predictions.

	10 ppm	100 ppm	400 ppm	1,000 ppm
Width	14.9 m	13.8 m	13.1 m	12.4 m
Depth	2.3 m	1.96 m	1.74 m	1.62 m
Velocity	0.58 m/s	0.80 m/s	0.88 m/s	1.00 m/s
Slope	0.000055	0.000172	0.000231	0.000387

The sensitivity of some of the parameters, particularly the slope, to sediment load can be observed.

9.1.3 Application of regime theory to natural rivers

The original development of regime theory was for the design of canals but subsequently the issue was raised whether it was also applicable to natural channels. The application to rivers is complicated by the definition of the discharge. In canals the range of discharges that are experienced is normally relatively limited but in natural channels there is normally a much wider range of flows. The difficulty then was to determine which was the appropriate discharge to use in the regime equations. For a given river it is always possible to define a given discharge that, when inserted into the equations, will give the correct value of width, depth or slope. This discharge is normally known as the dominant discharge. The difficulty is to provide an independent method of determining this discharge.

A number of methods have proposed including,

a) bankfull discharge,
b) discharge with a given fixed return period
c) mean annual flood,
d) the maximum sediment transporting discharge.

The maximum sediment transporting discharge is based on the concept that there is a discharge that contributes more sediment transport to the total annual sediment movement than any other discharge. Larger discharges have correspondingly larger sediment concentrations but as they occur less frequently do not contribute as much to the annual total. Lower discharges occur more frequently but the sediment concentration is smaller and so they do not contribute as much sediment to the total sediment load. To determine the maximum sediment transporting discharge one needs to know the flow exceedance curve for the location and the sediment concentrations corresponding to each discharge. The maximum sediment transporting discharge is the most attractive definition of the dominant discharge but the one that is most difficult to determine. To date the evidence as to whether it provides a better estimate of the dominant discharge than the other definitions given above is equivocal (Hydraulics Research 1986).

9.1.4 Implications for channel design and maintenance

Since regime theory appears to be applicable to natural rivers, it suggests that, for any given discharge and sediment conditions, there is a natural channel size and shape. If the channel is not of this size and shape then erosion or deposition will take place to alter the channel to more closely approximate the regime conditions. Thus in channel design, the designer is not always free to select the channel geometry and ideally should be guided either by the size and shape of the natural unconstrained river or by regime theory to determine the appropriate geometry of the channel. Failure to do this may lead to significant erosion or deposition and corresponding maintenance problems.

If the discharge in a river is altered, either by abstraction or by water transfer, then its size and shape are likely to respond. Thus downstream of dams a reduction in channel size is commonly observed as the river adjusts to reduced flows. Meanwhile in river diversion or transfer schemes in which the flow in the river is increased, there is usually an increase in channel size.

As there is a natural channel size and shape for a given discharge, which is dictated by the natural processes, if there is an engineering intervention which alters these then the river is likely to respond. Thus if a channel is widened or deepened with no other alterations to the flow regime then the natural processes will tend to act so that the river reverts to its original size. If a channel is constricted or narrowed, then protection is likely to be required to maintain the constricted reach.

9.2 Natural Channel Patterns

Channels have a ‘natural’ plan form in terms of sinuosity, meander wavelength, meander amplitude.

9.2.1 Classification of channel plan forms

If viewed on a geological timescale most rivers move and adjust their plan form, though the rate of change varies widely, depending upon the nature of the flow and sediment conditions. On an engineering timescale of perhaps 100 years, the amount of change can vary widely from river to river. The rate of change of lowland rivers in the UK may be very modest but in other areas of the world the changes can be large and rapid. It has been reported that reaches of the Yellow River in China have moved laterally by as much as 1 km overnight. Even within the UK it may not be safe to assume that the channel plan form will remain fixed during the lifetime of a structure and the possibility of plan form change should be considered during the design process.

The wide variety of naturally occurring channel plan forms are normally classified into one of three categories:
- straight,
- meandering and
- braided.

These are shown in Figure 9.1. The distinction between straight and meandering is slightly arbitrary and different authorities distinguish between the two in different ways. Different rivers meander by different amounts. To describe this a measure of the degree of meandering is introduced, called the sinuosity, which is the ratio of the channel length between two points and the straight line distance between the same two points. The sinuosity of straight rivers is thus 1. As a river meanders more and more the sinuosity increases.

Braided rivers have multiple channels. A feature of braided channels is that the individual channels are subject to large and rapid change. An individual channel may increase or decrease in size, move laterally or on occasions completely disappear. The overall character of the river in terms of the number of channels and complexity of the channel pattern is normally relatively constant.

Field measurements on a gravel, braided river have indicated that the size and shape of individual channels agrees well with regime theory but that the flows in individual branches vary as the channels upstream and downstream move and change (Thompson, 1987).

9.2.2 Theory of plan form

Initial attempts to predict channel plan form were based on empirical slope-discharge relationships, see Figure 9.2, (Leopold and Wolman, 1957, Lane 1957, Ackers and Charlton 1970 and Henderson 1963).
The following equations describe lines in the S-Q plane to distinguish the different river forms.

Leopold and Wolman (1957)

$$S = 0.012\ Q^{-0.44}$$

Braided channels plot above the line and meandering channels plot below the line.

Lane (1957)
For meanders $S = 0.0007\ Q^{-0.25}$
For braided channels $S = 0.004\ Q^{-0.25}$

Ackers and Charlton (1970)

Straight channels $S < 0.001\ Q^{-0.12}$

Straight channels with alternating bars

$$0.001Q^{-0.12} < S < 0.0014\ Q^{-0.12}$$

Meanders $\qquad S > 0.0014\ Q^{-0.12}$

The above equations are empirically based and do not take account of the impact of sediment size or sediment load. They also fail to take into account that the nature of a

Figure 9.1 Different types of river plan form

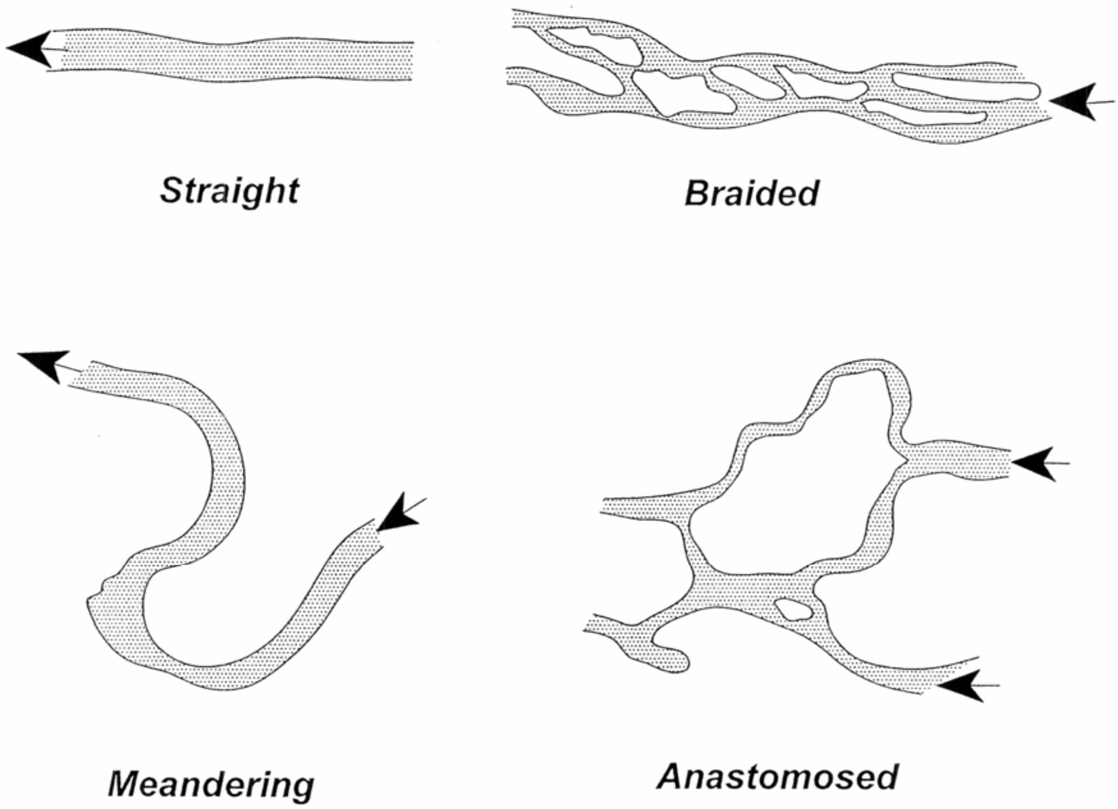
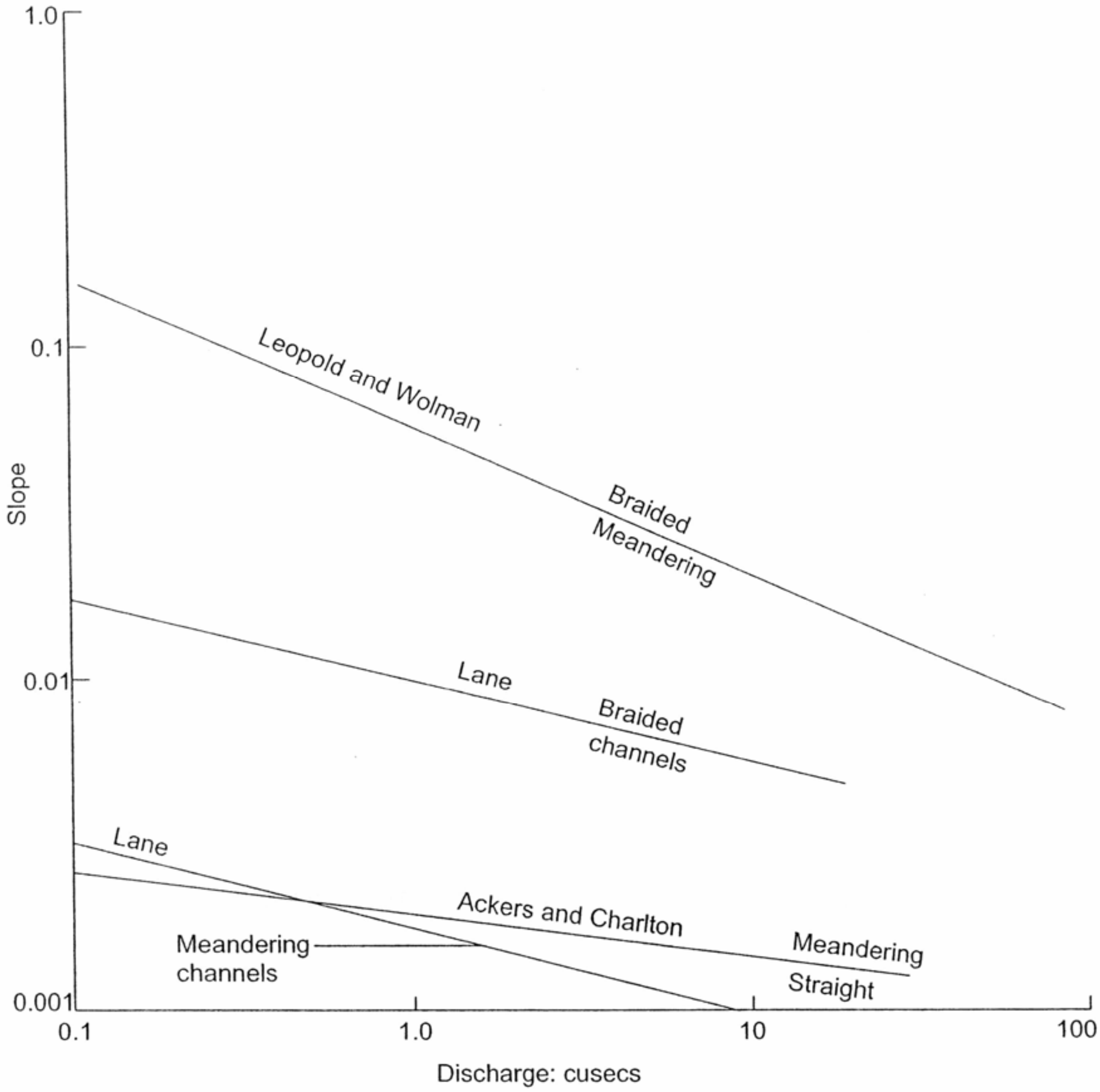


Figure 9.2 Empirical slope-discharge approach to predicting river plan form



river may be different at different discharges. Thus though they may be useful indicators of trends they cannot be relied upon for design purposes.

All the derived relationships differ but there is general agreement that braided channels occur at steeper slopes than meandering and meandering channels at steeper slopes than straight channels. The implication seems to be that the channel pattern progresses from straight to meandering to braided with increasing power.

Theoretical and laboratory studies have suggested that the plan form of a river is related to the discharge, sediment size, sediment load of the river and the valley slope (Bettess and White, 1983). Laboratory experiments have suggested that if the valley slope is similar to the regime slope for the given discharge and sediment properties then the plan form of the channel will be approximately straight. If the valley slope is steeper than the regime slope then the channel plan form will be meandering and the sinuosity will be approximately the ratio of the regime slope and the valley slope. In general the sinuosity is usually a little less because of the extra headloss generated at the meander bends. If the difference between the valley slope and the regime slope is large enough a threshold is crossed and the plan form becomes braided. The empirical curve derived by Leopold and Wolman describes this threshold but Bettess and White have produced a regime based explanation. Bettess and White argued that the channel braids when the valley slope reaches the slope corresponding to a regime channel carrying a third of the overall channel discharge. In this situation the difference between the valley slope and the regime slope can be accommodated by meandering with a high sinuosity or by dividing into a number of channels, see Figure 9.3. The notation in the figure is as follows:

S_{R1} corresponds to the regime slope carrying the total discharge,

S_{R2} and S_{R3} correspond to the regime slopes for channels carrying one half and one third of the total discharge.

Figure 9.4 gives a sample figure showing the implications for such a theory for predicting plan form.

Examples of change in plan form that might result from changes in discharge

a) Effect of an increase in discharge on channel plan form

If the discharge in a channel is increased, perhaps as the result of a water transfer scheme, then the regime slope of the river will decrease. The overall valley slope will remain the same and so there will be a tendency for the channel pattern to adjust. In a river that is already meandering, the difference between the valley slope and the regime slope will increase and hence the sinuosity will increase and may even begin to braid. In a braided river the braiding may become more intense.

b) Effect of a decrease in discharge on channel plan form

If the discharge in a channel is decreased, perhaps by construction of a dam, then the regime slope of the river will be increased. The overall valley slope will remain the same and so the channel pattern will adjust. In a meandering river the sinuosity will decrease. In a braided river the braiding may become less intense or the channel may change to a meandering form.

Figure 9.3 River plan form as a function of valley slope

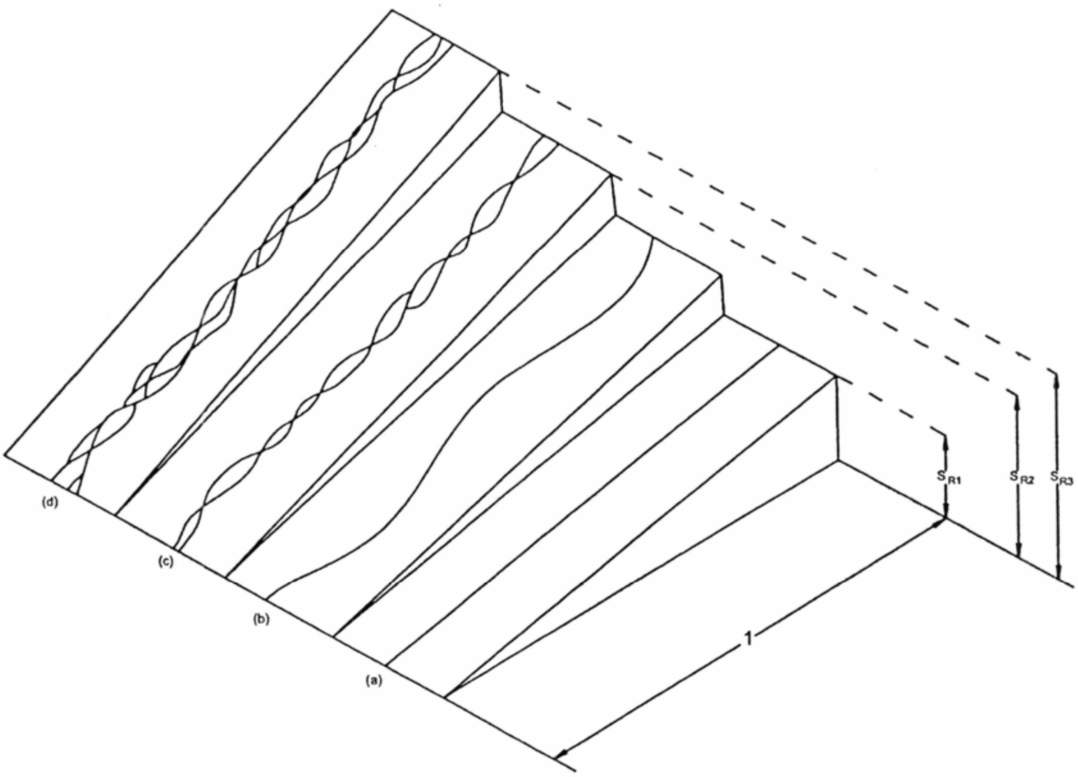
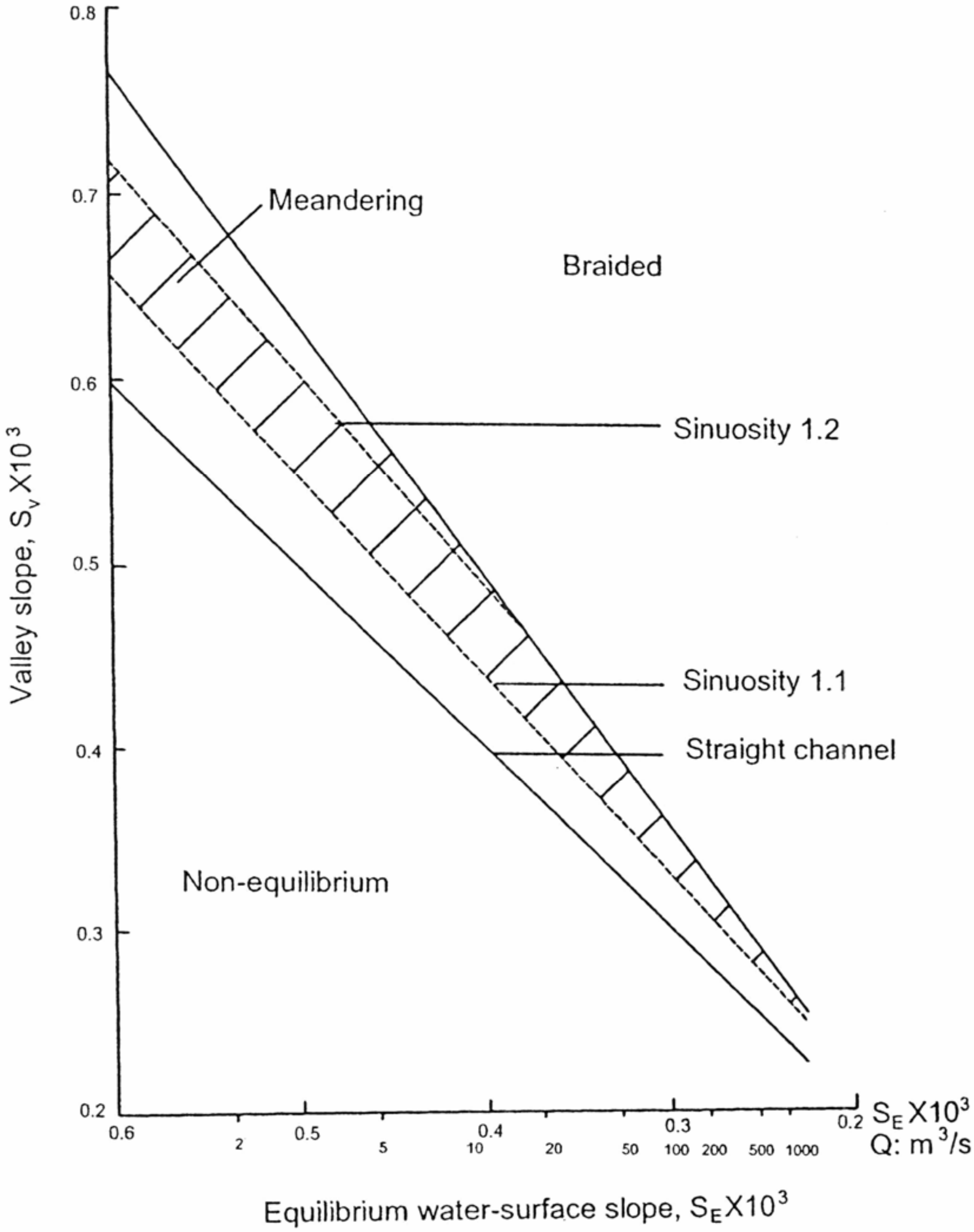


Figure 9.4 Predicting river plan form using rational regime theory



While there are methods available to predict the likely overall channel pattern, the precise details of the plan form are likely to depend upon local effects. Information on past changes can normally be derived from historical data sources. The most often used sources are historic maps and satellite imagery though a wide range of techniques is potentially applicable in particular cases, including archaeological excavation and dating techniques. In some cases old river courses are preserved in land or administrative boundaries.

9.2.3 Meander geometry

The meander geometry in terms of wavelength and amplitude is not arbitrary but related to the magnitude of the river. Empirical relationships have been derived relating the meander geometry to the bankfull discharge or the bankfull channel width.

Let M_l denote the meander wavelength: M_b the meander amplitude, Q_b the bankfull discharge and B_b the bankfull width. The following empirical relations have been derived:

Rivers in floodplains

Inglis (1949)

$M_l = 53.6\ Q^{1/2}$ or $M_l = 6.06\ B_b$

$M_b = 153.4\ Q^{1/2}$ or $M_b = 17.38\ B_b$

Leopold and Wolman (1960)

$M_l = 10.77\ B_b^{1.01}$

$M_b = 2.7\ B_b^{1.10}$

Ackers and Charlton (1970)

$$M_l / d = 123 \left(\frac{Q}{d^2 \sqrt{\frac{\Delta\gamma_s}{\rho} d}} \right)^{0.376}$$

Inglis gives slightly different relationships for incised rivers.

Example calculation of meander geometry
If these equations are applied to the above examples we obtain the following results.
Example (a) The river discharge is 1000 m3/s and the regime relations above predicted a width of approximately 142 m. It follows that:

Inglis	Ml = 1695 m	or	Ml = 862 m
	Mb = 4850 m	or	Mb = 2472 m

Leolpold and Wolman
Ml = 1610 m and Mb = 630 m

Example (b) The river discharge is 20 m3/s and the regime relations above predicted a width of approximately 18.44 m. It follows that:

Inglis	Ml = 240 m	or	Ml = 112 m
	Mb = 686 m	or	Mb = 320 m

Leopold and Wolman
Ml = 204 m and Mb = 67 m

A number of things can be observed. Inglis gives two versions of the equations for Ml and Mb; these appear to be connected by a regime relationship of the form:
B = 8.8 Q0.5.
This is different from the regime relationship used above and so the two equations for Ml and Mb give very different predictions. The predictions of Ml by the Inglis equation based on Q and the Leopold and Wolman equation give similar results. The predictions of Mb vary significantly. For a given value of Ml the value the value of Mb depends upon the sinuosity. The above equations suggest that sinuosity depends only upon Q or B though it is not clear that this is true. As a result the values of Mb predicted by these equations should be regarded with suspicion.

The above equations are empirically based and at present we do not have sufficient knowledge of the physical processes to be sure what are the dominant physical parameters. In this situation the above equations should be used with caution. They probably indicate the order of magnitude of the relevant variables but they should not be regarded as precise predictors.

Note that regime theory would suggest that the bankfull discharge and the bankfull channel width are related. Thus in restoring the meander pattern in a previously straightened reach of river, the sinuosity, meander wavelength and meander amplitude cannot be selected arbitrarily but need to be selected to be appropriate to that reach of river.

9.2.4 Development of channel plan form

The plan form of a river is not fixed for all time and in most cases it is natural for it to change through time. On a geological timescale most rivers are subject to major movement. On an engineering timescale most rivers are subject to some change though the amount of change may be highly variable. The plan form of active rivers may alter substantially in short time periods. A reach of the Yellow River in China is reported to have moved laterally by up to 1 km over night. In other rivers there can be little observed change over periods of hundreds of years.

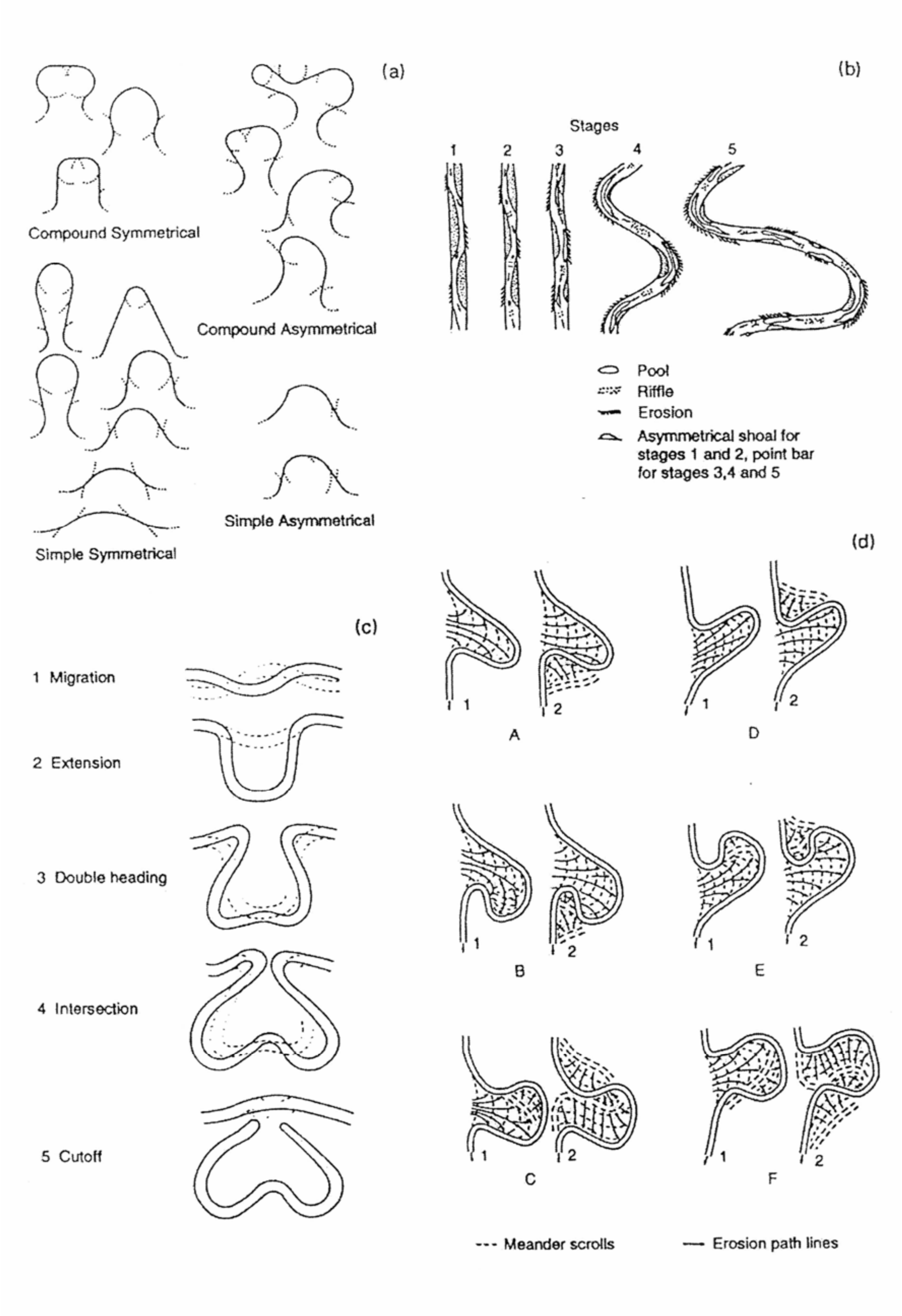
In a meandering river there is a tendency for the meanders to move downstream. There are a few measurements of the rate of migration, see Table 9.1 but there are no theories to predict the migration rate. It is likely that the migration rate will vary through time depending upon the sequence of flood flows.

Table 9.1 Rate of lateral migration of rivers

River and location	Total movement	Period of change	Rate of movement
	(m)		(m/year)
North River at	128	1834-1884	2.45
Parnassus Quadrangle,			
Virginia, USA			
Seneca Creek,	0 to 3.0	50-100	0 to 0.06
Dawsonville,			
Maryland, USA			
Larami River	30	1851 –1954	0.3
Wyoming, USA			
Ramganga River,	885	1795-1806	80.5 (westwards)
India	320	1806-1883	4.3 (eastwards)
	241	1883-1945	4.0 (westwards)
Colorado River,	6100	1858-1883	244
California, USA			
Missouri River,	1525	1883-1903	76
Nebraska, USA			
Mississippi River,	726	1930-1945	48
Mississippi, USA			

An individual meander bend may migrate or develop or do both. Much work has been done on the description of different forms of meander bend development but there is little to indicate how a particular meander bend may develop in the future, see Figure 9.5. A meandering channel may develop by lateral channel shifts or it may change by suddenly adopting another course, known as avulsion. Whether an avulsion occurs or not depends upon the local conditions. When it does occur, the change is frequently rapid and can often be associated with a major flood.

Figure 9.5 Case studies and models of sequences of meander change



As explained above, a feature of braided channels is that individual channels are subject to large and rapid change. An individual channel may increase or decrease in size, move laterally or on occasions completely disappear. The overall character in terms of the number of channels and complexity of the channel pattern is, however, normally relatively constant.

9.2.5 Prediction of future development of plan form change

There is often an interest in predicting the future plan form of a river reach. This may be important in assessing the need, if any, for river training works. If such works are required then an assessment of the future plan form of the river will be important in determining the nature of any training works. The future plan form will also affect what flow velocities river structures may be subject to in the future.

There are very limited methods available to predict future plan form change. If historic data is available it is usual to extrapolate from this to indicate likely future changes. Data has been collected on the rates of migration of meander bends but without a comprehensive theory of the meander bend movement it is difficult to use such measurements to predict the future rate of movement of other meander bends. Some attempts have been made recently to produce numerical models of channel plan form (Howard, 1996). Such models are encouraging as they produce output that appears to be sensible but there appears to have been little work done to verify such models against field data. As a result, at the moment, these models can only be regarded as research tools.

The prediction of future planform changes is the subject of active research. So far models have been developed but in general their validity has not been established by comparison with historic plan form change. They thus cannot be used with any confidence to predict future changes.

The temporal movement of a meandering river may be strongly affected by inhomogeneities in the floodplain sediments and the presence of hard points or less erodible areas of material (Thorne, Hey and Newson, 1997). Unfortunately, the presence of such areas of higher resistance to erosion are often difficult to detect until the development of the river is visibly affected. Thus including their impact in predictions of future change is often difficult or impossible.

9.2.6 Plan form as a function of discharge

Though the topography of a river may remain constant, the observed plan form, as displayed by the shape of the flooded outline, may vary with discharge. Thus, typically, a river that has a high sinuosity at low discharges will have a lower sinuosity at higher discharges and a river that appears braided at low discharges may appear single-thread at higher discharges.

9.2.7 Implications for channel design and maintenance

In designing a new channel the appropriate plan form should be considered. Failure to do this may lead to excessive bank erosion and a high maintenance commitment. To avoid these problems, the channel plan form should be selected to correspond with the proposed discharge, equilibrium slope, valley slope and sediment size and load.

In carrying out works on a river attention should be paid to any changes in plan form and particularly plan form characteristics. If a particular reach is lengthened or shortened then there is a tendency for the river to modify its course to re-establish the previous plan form characteristics. Thus if a meandering reach of river is straightened then bank erosion on alternate banks is likely to take place which, if left unchecked, will re-establish a meandering course. If a channel is straightened, therefore, it is usually necessary to carry out bank protection works to ensure that the modified course is preserved in the future or to introduce low drop structures to help to maintain the new straightened course.. Failure to do this often results in the river adopting its previous plan form over a period of time. If the river plan form is changed but the original plan form characteristics such as sinuosity and wavelength are retained then it is likely that future bank erosion and maintenance will be reduced.

9.3 Bank Erosion

9.3.1 Introduction

Changes in channel plan form and channel size or shape normally occur as a result of bank erosion and sediment deposition. Though in many rivers the processes of bank retreat and bank advance take place at approximately equal rates, it is normally bank retreat in the form of bank erosion which is the most obvious and which generates the most concern.

As part of the design of bank protection schemes, it is extremely important to identify the correct mechanisms that are causing, or might lead to, bank erosion in order to design appropriate bank protection measures. Failure to do this may lead to rapid failure of the bank protection. In extreme cases the bank protection may precipitate the bank failure that it was designed to prevent. The Environment Agency Report (Environment Agency, 1996) gives a procedure for assessing river bank erosion problems and solutions.

Bank erosion can take place due to a number of different causes:

- 1) Bank weakening processes
  - 1.1) Dessication
  - 1.2) Freeze-thaw action
- 2) Fluvial erosion processes
  - 2.1) Direct entrainment of particles by flow
- 3) Mass failure mechanisms
  - 3.1) These include various forms of slip failure

The factors which influence bank erosion processes include:

- Sub-aerial processes
  - Micro-climate
  - Bank composition
- Fluvial processes
  - Stream power
  - Shear stress
  - Secondary currents
  - Bend morphology
  - Vegetation
  - Bank moisture
- Mass failure
  - Bank height
  - Bank angle
  - Bank composition
  - Soil pore water pressure

9.3.2 Dessication

Even in the UK, river banks can be subject to rapid heating and extremes of temperature. This may be associated with the spalling of surface materials and even in some circumstances the removal of slabs of material (Lawler, 1992). The impact of dessication on river banks depends upon the soil type. Some banks will dry and the resulting crust will be more resistant to fluid entrainment during later floods. In other soils, dessication will lead to spalling and the direct removal of material or it will lead to cracking. Such cracking will reduce bank strength and lead to easier mass failure. Cracking also enhances movement of water into and out of the bank during subsequent floods and hence affects pore-water pressures.

9.3.3 Freeze-thaw action

In cool and temperate climates the river bank may be subject to freeze-thaw action. This can break up the soil structure of the bank and lead to soil erosion. The magnitude of this effect is very dependent upon the local climate but in small river it can represent a significant source of bank erosion.

There are particular forms of such bank erosion associated with both permafrost and also with the action of rafts of ice during the spring thaw.

9.3.4 Fluvial erosion processes

Fluvial erosion is caused when the shear stress exerted by the flow on the bank material exceeds the resistance of the bank material. Such fluvial erosion can contribute to bank erosion in two ways. Material may be directly removed form the bank and transported downstream or fluvial erosion may remove bed material from the base of the bank, initiating a mass failure of the bank, see below. Weakening or weathering of the bank material may make it more vulnerable to fluvial erosion.

9.3.5 Mass failure

Mass failures can occur in cohesive banks due to slip failures in which the gravitational forces exceed the cohesive strength of the bank. The form of the slip will depend upon the detailed geometry of the bank but under suitable conditions deep seated slips can occur. Cracks and fissures in the bank can significantly reduce its stability. Mass failure normally results in bank material being deposited at the foot of the bank which tends to stabilise it. If the flow induced shear stress at the toe of the bank is large enough, this material will be entrained into the flow. If, as the result of this erosion of the toe, the bank configuration returns towards its pre-failure state then a further failure of the bank may be precipitated. Thus the flow conditions at the toe of the bank are an important factor in controlling whether further bank erosion takes place. This has been referred to as 'basal end-point control'.

In banks of non-cohesive material in which the material is only partially saturated then the pore water pressure can be negative (capillary suction) thus imparting an apparent degree of cohesion to the banks. Thus in many circumstances a non-cohesive bank may behave in the same way as a cohesive bank.

9.3.6 Influence of geological constraints

Geological constraints may influence the longitudinal profile of a river or may affect its plan form. A waterfall arising as the result of a band of inerodible rock may be found on many rivers. This is a very clear constraint on the development of the longitudinal profile of a river. Geological constraints on one or both sides of a river channel may also limit the lateral movement and plan form of a river.

9.3.7 Impact of structures on stabilising either bed level or plan form

Hydraulic structures may stabilise the plan form of a river. Probably the most common form of such a structure is a weir. This stabilises the bed level of a river immediately upstream of the weir. The same may be achieved by geological constraints on the bed of a channel. The plan form of a river may also be stabilised by the presence of structures. River training works can control both the location of a channel and the flow direction. Other structures, though not designed to control the plan form, may inhibit channel movement at particular locations. Thus a weir, bridge or barrage may prevent lateral channel movement but may allow changes in the angle of approach. Again the same may be achieved by the presence of geological constraints.

In designing structures, particularly on meandering or braided rivers, it should not be assumed that the plan form of the river in the neighbourhood of the structure will not change during the design life of the structure. For example, a bridge was built approximately 100 years ago and the piers were well aligned with the flow. During the intervening period the meander pattern has progressed downstream. The river is constrained to pass under the bridge but the angle of approach has altered by approximately 90 degrees. The result is that the piers are now very poorly aligned with the flow. Presumably in approximately 100 years time the piers may well be well aligned with the flow once more.

Plan form problems may be experienced immediately upstream of reaches whose plan form has been stabilised by river training or other means. Though the plan form of a reach of a river may have been fixed, the reach upstream may continue to adjust naturally. This may result in a short transition zone between the two where there may be extreme developments in the plan form.

In some parts of the world tectonic activity may have a significant impact on the slope of the river. This will then also significantly affect the plan form of the river.

9.4 Deposition in Reservoirs

Reservoirs on rivers are characterised by cross-sections that are larger than the average cross-section of the river. As a result the water surface slope and velocity are reduced. This means that a proportion of the sediment transported by the river will be deposited in the reservoir resulting in loss of storage and a wide range of other environmental effects. Reservoir sedimentation can lead to:

- a loss of storage,
- increased flooding risk upstream,
- reduced water depths at the head of the reservoir, this can in turn lead to:
- increased evaporation losses,
- increased water levels upstream,
- reduced navigation depths,
- increased vegetation in the upper part of the reservoir which can lead to:
- increased transpiration
- trapping of increased amounts of sediment.

Rates of loss of storage can be high. One reservoir in the USA substantially filled with sediment within a year of construction. On average 2 to 3 % of the storage in the world's dams is lost through sedimentation each year. This represents a large economic cost. In the UK loss rates are generally smaller but some of the older UK dams have lost significant amounts of storage.

There are a number of methods for predicting the rate of reservoir sedimentation. The simplest methods are desk based and are based on the idea of trapping efficiency. This is the proportion of sediment that is trapped by a reservoir in relation to the overall volume of sediment entering the reservoir. When first introduced the trapping efficiency was based on figures collected over a number of years but HR Wallingford extended the concept of trapping efficiency to other time periods. One can thus consider an instantaneous trapping efficiency or a trapping efficiency derived over a month or other time period.

The amount of sediment trapped in a reservoir depends upon both the flow into the reservoir and the size of sediment. The most important flow related parameter is frequently the residence time, that is the average period of time that the water spends in the reservoir. If this is large then most of the sediment will settle in the reservoir but if it is short then a greater proportion of the sediment will be transported through the reservoir. This is affected, however, by the size of the sediment. For the same residence time a larger proportion of coarse sediment will deposit than fine sediment because of the larger fall velocity of coarse sediment.

The trapping efficiency can be estimated using simple desk methods. Brune (1953) derived curves that described trapping efficiency as a function of the capacity of the reservoir to the annual inflow. Reservoirs for which the capacity approaches or exceeds the annual inflow effectively provide over year storage and their trapping efficiency normally approaches 100%, that is, they trap all the incoming sediment load. As the ratio of capacity to annual inflow reduces the trapping efficiency reduces. Churchill (1948) expressed the trapping efficiency as a function of a sedimentation index, which is the ratio of the period of retention to the mean transit velocity.

Both these desk approaches give quick simple methods of assessing the volume of sedimentation but they ignore many important factors, such as sediment size, annual flow distribution and the shape of the reservoir. HR Wallingford introduced a desk-based computational procedure that was aimed at overcoming many of these shortcomings (HR Wallingford, 1989).

Alternatively a numerical model can be used to predict reservoir sedimentation. Such models can be used to provide information on:

- the distribution of sediment deposits within the reservoir,
- the composition of the deposited sediment,
- revised stage storage curves for the reservoir,
- the impact on water levels upstream.

Reservoir sedimentation models can also be used to investigate strategies for reducing the loss of storage by, for example, the use of sediment flushing. Practical experience has shown that flushing can preserve storage in reservoirs but it is only practicable in limited circumstances (White and Bettess, 1984).

9.5 Sediment Deposition on Floodplains

During floods sediment is transported in the main channel. Either by diffusion or convection this sediment is carried onto the floodplain and, as the flow velocities on the floodplain are generally low, it is deposited. The rate of sediment deposition normally reduces rapidly as one moves away from the main channel. Sediment deposition on floodplains is normally largest where there is an exchange of water between the main channel and the floodplain, commonly at bends.

Sedimentation rates of the order of 1gm/cm^2/year have been measured on UK rivers (Walling et al, 1996). Sedimentation rates of this order imply increases in bed level of the order of 1cm/year. If these rates of sedimentation persist for periods of the order of centuries then significantly increased bank heights may result together with floodplains that slope away from the main channel. Floodplain archaeology indicates, in general, much lower rates of accretion. The difference may well be due to the fact that in the past a river channel did not occupy the same location on the floodplain for an extended period of time. Within the last 100 years we have constrained some river reaches and it remains to be seen what the long-term impact is on the development of the river systems.

10 Environmental Issues

10.1 Characteristic Ecology of River Channels

The great majority of stream-dwelling macro-invertebrates live in close association with the substrate and so are strongly influenced by it. Many taxa exhibit some form of substrate preference and some organisms are quite restricted in the conditions that they occupy. Lithophilous taxa are those found in association with stony substrates. Many species are equally common on stones of all sizes but some are more likely to be found in association with a particular sediment size class.

An important aspect of the substrate is the frequency with which the sediment particles move. Larvae of the water penny occur mainly on the undersides of rocks and often under boulders. Attached and encrusting growth forms require a substrate that is not easily moved by the current. The longer the life span of the organism then the more critical this is. Diatom populations are greatly reduced by flows that scour and move substrates, although populations of these single celled organisms quickly recover. Slowly growing organisms like mosses and bryozoans are found mainly on larger stones or where sediment movement is unlikely.

The surface texture and chemical composition of the particles making up the sediment substrate may also affect the plant species that will grow on the particles. Thus the introduction of alien sediment should be avoided if possible.

Sand substrates are normally liable to frequent movement. The close packing of sand grains reduces the flow through the bed and hence limits the availability of oxygen and the trapping of detritus in the bed. For these reasons sand is in general a poor substrate for fauna. A variety of taxa, termed psammophilous, do, however, colonise sand beds. Small invertebrates, capable of passing through a 0.5 mm sieve, may be abundant and can live to considerable depths within sand substrates. Burrowing taxa tend to be specific in which sizes of sediment they can inhabit.

In general, diversity and abundance of benthic invertebrates increase with median particle size, while some evidence suggests that diversity declines with stones at or above the size of cobbles.

Fish are normally not as constrained by substrate type but a number of invertebrate species tend to occur on or near particular substrates. At spawning, however, and for some time after hatching, many fishes of running water require particular substrate conditions. The majority of freshwater fish select hard substrate for reproduction and it is likely that availability of suitable substrate for spawning affects the distribution and abundance of many species of fish. During spawning and immediately after hatching, the fish population is particularly vulnerable to high flows. A flood shortly after spawning which moves the sediment among which the eggs have been deposited can lead to high rates of egg mortality.

Small amounts of silt may benefit some taxa but significant amounts of silt may change the substrate sufficiently to cause marked changes in the invertebrates present. Large amounts of silt fill the interstices between coarser sediments, thus reducing the exchange of gases and water and the habitat space available. Silt is normally also mobile under a wide range of flows. The result is that the presence of significant amounts of silt is generally detrimental to the macro-invertebrate life.

The presence of organisms within the sediment matrix can also influence sediment movement. A number of micro-organisms secrete material which can bind fine sediment particles together. Thus the presence of such organisms within a silt or fine sand bed can modify the sediment properties, generally by increasing the threshold of motion and reducing the sediment transport rate for small shear stresses. For larger shear stresses the disturbance to the bed may be so large that the presence of these micro-organisms has no effect.

An important factor in the abundance and diversity of species present is the presence or otherwise of detritus. Sediments are not themselves a source of nutrition and so the presence of organic detritus is an important aspect of the habitat. The size and type of detritus trapped within the sediment can also be a function of the substrate type. Thus smaller detritus tends to accumulate in sand beds whereas gravel beds tend to accumulate more sticks and twigs. The amount and type of detritus within the substrate may be an important factor in determining species type and abundance.

Salmon and trout deposit their eggs in gravel and the survival of these eggs depends upon the flow of water through the gravel as, if the flow reduces too much then the eggs will suffocate. When there is no fine sediment being carried by the water then a reasonable proportion of the eggs would be expected to survive. If there is fine sediment in the flow then the gravel on the stream bed tends to filter out the fine material reducing the permeability of the substrate and hence reducing the flow around the eggs. This can cause suffocation of the eggs.

Salmon and trout eggs survival can also be affected by the size of the substrate. These fish use quite a narrow size range of bed sediment in which to deposit their eggs. Changes to the sediment sizes on the bed may reduce the spawning area available and so adversely affect the fish population.

The abundance of food for particular species of fish may also be affected by the substrate. If the proportion of fine sediment is small then benthic macro-invertebrates like mayflies and caddis flies will predominate. The caddis fly and mayfly nymphs are important food for trout. As the proportion of fine sediment on the bed increases, the insect population shifts towards midgefly larvae, a food eaten mostly by suckers and similar bottom-feeding fish. Hence the fish population is sensitive to the macro-invertebrate population which in turn depends upon the nature of the substrate.

Thus it is clear that the bed composition and the frequency with which it moves can have a significant impact on the ecology of a river channel.

The morphology of a channel also affects the flow velocity and this can also have an impact on the ecology of a river. A flow velocity is beneficial in that it provides a continuous supply of gases and nutrients. The impact of flow velocity becomes adverse, however, as the flow increases due to its ability to remove species from their habitat. The distribution and abundance of particular plant species is dependent upon the flow conditions. In some species the growth form of the plant depends upon the flow velocity. Thus changes in the flow regime of a channel may have a significant impact on the ecology of a river.

The banks of a river also form an important habitat. Some of the same issues that are important for the substrate of a channel also apply to the banks. Erosion of banks can prevent the establishment of vegetation and so prevent the establishment of some eco-systems. Other species, for example sand martins, prefer to live in steep sandy banks that are subject to periodic erosion. The erosion of the banks introduces sediment into the river system. This may have an important effect on the ecology of the river either at the location of the bank failure or downstream. If the flow is unable to transport all the eroded bank material then bank debris will build at the base of the bank, which may smother the original bed sediments leading to a change in bed sediment composition and hence alluvial resistance. If the flow is capable of transporting the eroded bank material it will be transported downstream. It may be deposited some distance downstream and there lead to changes in the composition of the substrate and modify associated bed features.

It should be remembered that engineering work may lead to sediment changes over a long length of river. Thus the construction of a dam may lead to changes in bed composition that extend for tens or even hundreds of kilometres downstream. The impact of works may be physically separated by considerable distances from the location of the works. Changes in bed composition may lead to corresponding changes in alluvial resistance. If fine sediment is introduced into a river the primary impact may only occur where it is deposited which may be some considerable distance downstream of the point where it entered the river system.

10.2 Impact of Bed Features on River Ecology

The presence, size and shape of bed features affects the hydraulic roughness of a channel. This has a direct impact on the velocity and depth of flow. If the hydraulic roughness of the channel is low then the flow will be relatively shallow and fast. As the hydraulic roughness increases the flow becomes deeper and slower. As the flow characteristics in terms of depth and velocity are an integral part of the riverine environment changes in the flow conditions will have an immediate impact on the environment. Many fauna exhibit preferences for particular flow conditions. Changes in the flow conditions will have an effect on the available area of suitable habitat for different species and will hence influence both the range and abundance of species available.

Large bed features significantly modify the near bed velocity and shear stress distribution and so can have a significant impact on the ecology of a channel. Under certain flow conditions the flow can separate from the crest of a dune. This generates a turbulent mixing zone downstream from the crest, with a re-circulation zone near the bed. This has a significant effect on the velocities adjacent to the bed and the shear stress on the bed and modifies them considerably from the conditions without bed features. The impact of the bed feature is thus to modify the potential habitats and so to have an effect on the ecology of the stream.

An important factor for the ecology of the stream is the speed of movement of the bed feature. Where the speed of movement is large then organisms do not get an opportunity to colonise the bed but the slower the rate of change then the greater the opportunity for colonisation. The movement of some bed features depends upon the flow conditions. Particularly in gravel rivers, movement can be episodic and may only take place during large flows.

In certain river systems it seems that it is possible for large bed features to develop and propagate at small speeds. In the Meghna River in Bangladesh a large sand dune with an overall length of approximately 1km has been observed to be moving slowly downstream while on the River Lochy in Scotland a gravel bar approximately 30m long and 500 mm high appeared to be progressing downstream at a low rate. The gravel bar was observed to be moving over a surface that was supporting a range of plant and animal life. The material of the bar itself seemed sterile. In such cases the movement of large bed features can destroy existing habitats which may take some time to recover.

10.3 Water Quality

Where bed features are large enough and the flow is appropriate then the flow may separate from the crest of the feature. A re-circulation zone will then form in the lee of the crest. Such 'dead zones' can be important in the movement of pollutants through a river system. Dead zones act as temporary stores for pollutants, gradually releasing material after the peak of the pollution passes. This mechanism can attenuate and lengthen pollution concentration profiles downstream from where pollution has entered a river.

The presence of bed features on the bed of a channel will alter the pressure distribution on the bed of the channel, causing local variations. This may locally cause flow into or out of the bed. This will enhance the interchange of water between the channel flow and the water in the interstices of the bed sediment. In the presence of pollution this may enhance the movement of pollutants between the channel flow and the water in the bed of the river.

In many instances pollutants can become attached to the surfaces of sediments. If the sediments are then incorporated into bed features then this may temporarily remove them from contact with the flow in the river channel. As the bed feature moves, however, the polluted sediments may later be once again exposed to the flow. In this way bed material can act as a temporary store of pollutants. This can lead to the attenuation of pollutant plumes. The incorporation of polluted sediments into bed features may also make the clear up after pollution incidents difficult and reduce its effectiveness.

Within a river system there are many sources and sinks of sediment. These are of varying extent and the duration for which sediment is stored can vary significantly.

Storage location	Duration of storage
Bed features	Minutes to days
Deposition on bed of channel	Minutes to millions of years
Deposition on floodplain	Days to millions of years

Such stored sediment may be introduced back into the river system by:
- bank erosion or
- bed erosion.

In many river systems the transfer of sediment on to the floodplain can represent an important ‘sink’ for suspended sediments. Lambert and Walling (1987) measured the suspended sediment load entering and leaving an 11 km reach of the Lower River Culm in Devon, where the floodplain is regularly inundated during flood events. They estimated that approximately 28% of the suspended sediment entering the reach was deposited on the floodplain within the reach. Walling and Quine (1993) estimated that 23% of the total suspended sediment transported through the main channel system of the River Severn during the period 1986 to 1989 was deposited on the floodplain. Trimble considered the sediment budget for a 200 km^2 catchment of Coon Creek in the USA. He demonstrated that more than 50% of the sediment mobilized from the slopes of the basin during the period from 1850 to 1938 was deposited on the floodplain of the lower and middle valley and its tributaries. Thus significant amounts of sediment may be deposited on floodplains during out of bank flows.

Sediment deposition on the floodplain can act as a sediment sink and thus store contaminants. If agriculture is taking place on the floodplain then this may make the pollutant available for incorporation into the foodchain. At a later date these floodplain sediments may be released back into the river system by the process of bank erosion. Leenaers and Schouten (1989) have shown that recent streambank erosion on the river Geul in the Netherlands is mobilising substantial quantities of floodplain sediments contaminated with lead, zinc and cadmium which were mostly deposited during the peak of ore extraction in the catchment in the nineteenth century. 66, 47 and 39% of the lead, zinc and cadmium, respectively, that enters the channel is supplied by river bank erosion. Gold mining around Lead, South Dakota, USA, during the period 1870s to 1978, produced approximately 100 million tonnes of mine tailings contaminated with arsenic. It has been estimated that up to 15% of these tailings are still stored on the floodplain of a 164 km reach of river downstream (Marron 1987,1989). Thus floodplain deposits can be an important factor in the movement of pollutants through fluvial systems.

Bank erosion is the most important factor in the release of these pollutants stored on the floodplain back into the river system. Large and rapid plan form change can ensure that large quantities of floodplain material are released into the river. Thus the potential impact of excessive bank erosion on pollutant release and movement should be considered. The bank material of the Red River in Cornwall has a very high concentrations of arsenic as the result of industrial processes associated with extensive lead mining in the past. This means that any bank erosion has the potential to release large quantities of arsenic into the river downstream. Under these circumstances, the prevention of bank erosion may become more important than allowing the plan form of the river to develop naturally.

10.4 Habitat Hydraulics

The size of substrate can interact with the habitat in a number of ways. The size of substrate affects the hydraulic roughness of the channel and hence affects flow velocity and depth, which are major factors in the habitat. As discussed above, the size of substrate can also affect flora and fauna directly. This influence is considered, if somewhat crudely, in habitat models such as PHABSIM. The PHABSIM model simulates a relationship between stream flow and physical habitat for various life stages of a species of fish, benthic invertebrates or for a recreational activity such as canoeing. In PHABSIM the nature of the substrate is one factor which is considered explicitly.

11 Methods of Study of Sediment Problems

11.1 Introduction

There is no one universal method to study sediment problems that is appropriate for all types of problems. The appropriate method of study has to be chosen to match the nature of the problem and the type of information that is required. A number of different approaches are discussed below. They are not mutually exclusive and a number of different methods of approach can be used to look at different aspects of the same problem.

Type of problem	**Method of study**
Degradation downstream of dam	1-D numerical model
Reservoir sedimentation	1-D, 2-D and 3-D numerical models
Local scour	Physical model
Sediment movement at an intake	2-D/3-D numerical model
Diversion design	Desk calculations and 1-D numerical model
Irrigation canal	Desk calculations
Impact of river training works	Numerical models (1-D, 2-D or 3-D depending upon the level of detail required)
Predict future plan form of river	Desk method

Desk methods are normally quick, easy to apply and cheap. If a river is currently in equilibrium and the interest is to predict a new equilibrium that will arise from some change to the river system then desk methods can be extremely useful. In general, they cannot indicate the rate of change, however, and it is difficult to use them to predict variations along a river reach.

Numerical models can be used to look at both variations along the length of a river and the rate of change. There are different degrees of complexity and expense for the different spatial descriptions. Mobile-bed one-dimensional river models are now routinely applied and appropriate software is readily available. Two and three dimensional models are more expensive to apply, require significantly larger amounts of data and their application is more specialised.

Physical models can be very good at reproducing sediment behaviour though they suffer from a number of disadvantages, mostly relating to scaling, which normally restrict their application to relatively short reaches of river.

11.2 Desk Methods

Desk methods are normally appropriate where there is only interest at one location in a channel or where one is interested in the overall character of a channel and not interested in variations along the length of the channel. They can be used to look at problems of initiation of motion, that is, to assess whether, at a particular location, sediment of a given size will move under a given flow, see Chapter 5.

They can also be used to assess the type of sediment movement that is taking place, that is, whether under a given flow a particular sediment will move as bed load or suspended load, see Figure 3.6. For suspended load the variation of sediment concentration through the depth can also be predicted, see Figure 3.7. Desk methods can also be used to predict the sediment concentration or amount of sediment in motion, see Chapter 6.

In applying desk methods to the above problems it should be realised that conditions can vary quite significantly from one section to another along a river reach. In channels with mobile beds there can be significant changes in bed level and channel form over distances of a few channel widths due to the impact of bends, sediment bars and bed features. Thus there may be dangers in assuming that calculations at one cross-section are representative of a whole reach. It must be remembered that, in general, the sediment concentration calculated for flow conditions averaged over a number of cross-sections will not correspond to the sediment concentration calculated at each cross-section and then averaged. To be confident that the impact of variations from section to section are being taken into account it may be necessary to use a numerical model which can represent a reach of a river rather than just a single cross-section.

Desk methods can be used:

i) to determine alluvial resistance and the variation of alluvial resistance with discharge,

ii) to predict the size and shape of stable alluvial channels. These methods are useful in determining overall sizes and shapes but, as described above, particularly in natural channels, there may be variations about these mean values.

Desk methods are also the only means that we currently have available to assess plan form problems. Plan form models are currently being developed but they are still research tools rather than models that can be confidently used in practise.

11.3 Numerical Models

11.3.1 Introduction

A one-dimensional, mobile-bed, numerical model is good at studying a long reach of a river and can be used to make predictions of morphological change over long time periods up to and in excess of 100 years. As with all one-dimensional models they cannot predict variations across a cross-section or variations through the depth. If information on such variations is required then one needs to resort to two or three dimensional models, which normally use a finer computational grid or mesh than one-dimensional models. They can thus provide more detailed spatial discrimination but they have to use a correspondingly shorter timestep and so cannot be used to make long-term predictions.

Two and three-dimensional models are good at providing spatial detail in complex local problems and for many such problems they are the only realistic method of approach. They do, however, suffer from a number of disadvantages:
- they require a lot of geometric data,
- they are currently difficult to use and normally require specialist operators,
- due to timestep constraints, it is currently difficult to simulate long time periods

It is expected that as hardware and software develop in the future the last two problems will reduce in significance.

11.3.2 One dimensional models

One-dimensional models represent the geometry of a reach of a river by using a sequence of channel cross-sections. The model operates using values of variables averaged over each cross-section, for example, average depth and average velocity. The models are time-stepping models in which the conditions at one instant are used to predict the conditions a short time later. By repeating this process predictions can be made any period of time into the future. In each timestep a flow calculation is carried out to determine the velocity, depth and water surface slope. Using this information and data on bed sediment size the sediment transport at each cross-section is calculated. By calculating the sediment transport rate at each cross-section and applying a sediment continuity equation it is possible to predict the changes in bed level at each cross-section at each timestep. It is thus possible to predict long-term changes in bed level over periods up to and in excess of 100 years.

One-dimensional models are useful for studying long lengths of rivers or simulating long time periods. For these types of problems then presently one-dimensional models are the only tools that we have available. The present restrictions of computer speed mean that two and three-dimensional models can normally only be applied to relative short lengths of river and can only simulate relatively short time periods.

Typical information that a one- dimensional numerical model can provide includes:
- change in bed level at a given cross-section over a given time period,
- volume of sediment deposited between adjacent cross-sections during a given time period,

- sediment concentrations at a given cross-section for a given flow,
- sediment volumes passing a given cross-section during a given time period.

If the numerical model is capable of distinguishing the movement of different sediment sizes then additional information can be provided including:
- composition of sediment in motion,
- composition of sediment on bed of channel,
- composition of deposited sediment.

These types of models have been applied to investigate problems such as:
- bed level changes downstream of a dam,

- bed level change in a main channel and flood relief channel as the result of the construction of a flood relief channel,
- bed level change as the result of the construction of flood embankments,
- bed level change as the result of increased flow in a canal,
- reservoir sedimentation.

There are a number of commercial packages available, normally linked with a river flow model, which include one dimensional, numerical mobile-bed modelling.

Example 1: Simulation of degradation downstream of a dam.

A one-dimensional mobile-bed numerical river model was applied to a reach of the Middle Loup River immediately downstream of the Milburn Dam in Nebraska. The dam was completed in May 1956. The US Bureau of Reclamation carried out a study of aggradation and degradation associated with the dam that provided cross-sections of the river at a number of sites and details of the sediment and discharge in the river. Surveys were carried out in June 1961 and June 1964. The reach that was simulated was 5.2 km long. The observed and predicted bed levels are shown in Figure 11.1. It can be seen that the agreement between the predicted and the observed degradation is excellent. No data was available on the change in sediment composition of the bed surface downstream of the dam but this was simulated in the model. Figure 11.2 shows the type of prediction of changes in bed surface composition that can be made by including multiple sediment sizes within the model..

Example 2 Reservoir sedimentation

Tarbela reservoir is a major reservoir that was constructed on the River Indus in Pakistan in the 1970s. Since its construction it has been subject to sedimentation. In 1997 a study was carried out to investigate options for maintaining the storage within the reservoir. A one-dimensional mobile-bed numerical model was used to simulate historic sedimentation in the reservoir and then this was used to investigate the impact of different options for preserving the reservoir storage. One of these involved the use of sediment flushing techniques. Figure 11.3 shows a longitudinal profile of bed levels along the reservoir and compares measured historic profiles with model predicted profiles. It can be seen that the model results give a good agreement with the observed profiles and so one can be confident that the model is simulating the dominant physical processes within the reservoir. Such models provide excellent tools to predict future sedimentation and to assess the impact of changes in the reservoir operation.

11.3.3 Two and three dimensional models

One-dimensional models only utilise section-averaged variables and so cannot predict conditions across a cross section or variations through the depth. They thus cannot predict changes across a section. If such variations are important one must resort to two or three-dimensional models. These models can provide much more spatial detail but normally cannot be used to simulate as long reaches or as long time periods as one-dimensional models. They can be used in conjunction with one-dimensional models by using a two or three-dimensional model to simulate a short reach within a longer reach that is simulated using a one-dimensional model.

Such two and three dimensional models can take account of variations either horizontally or vertically. This may be important where:

- there are significant lateral variations, for example, where sections are non-uniform or where flow is being abstracted at an intake,
- there are significant vertical velocities, for example, for flow around a structure such as a bridge pier,
- the vertical variation of sediment concentration is significant, for example, at intakes.

In situations in which the vertical variation in suspended sediment concentration are important then two and three dimensional models are the only effective tools that are available. One dimensional models cannot directly predict such variations as they deal in section-averaged values and the scaling of sediment in physical models normally means that representation of the vertical suspended sediment concentration profile in physical models requires physical models that are impracticably large.

Figure 11.1 Observed and predicted degradation downstream of a dam

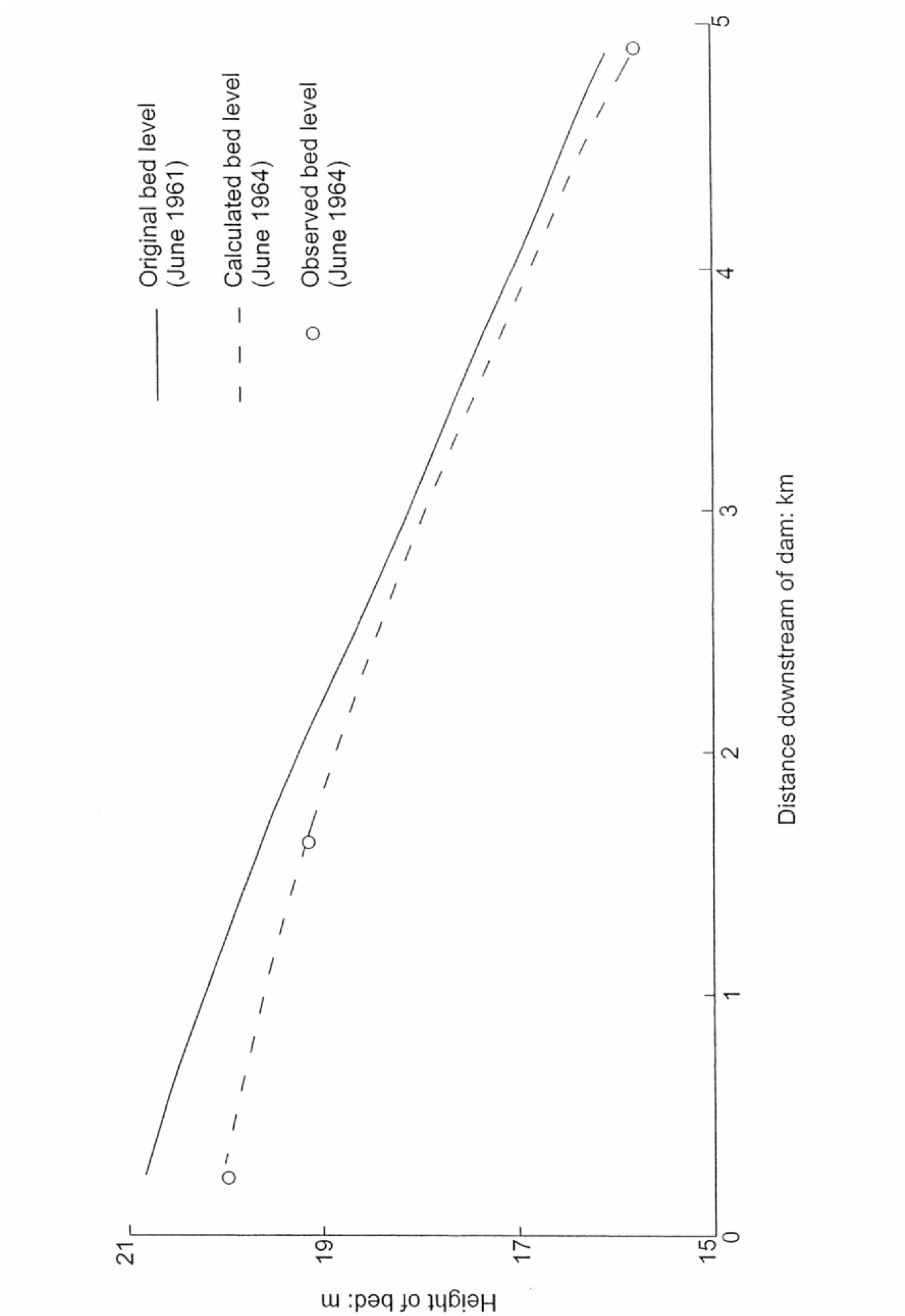


Figure 11.2 Prediction of changes in bed composition during degradation downstream of a dam

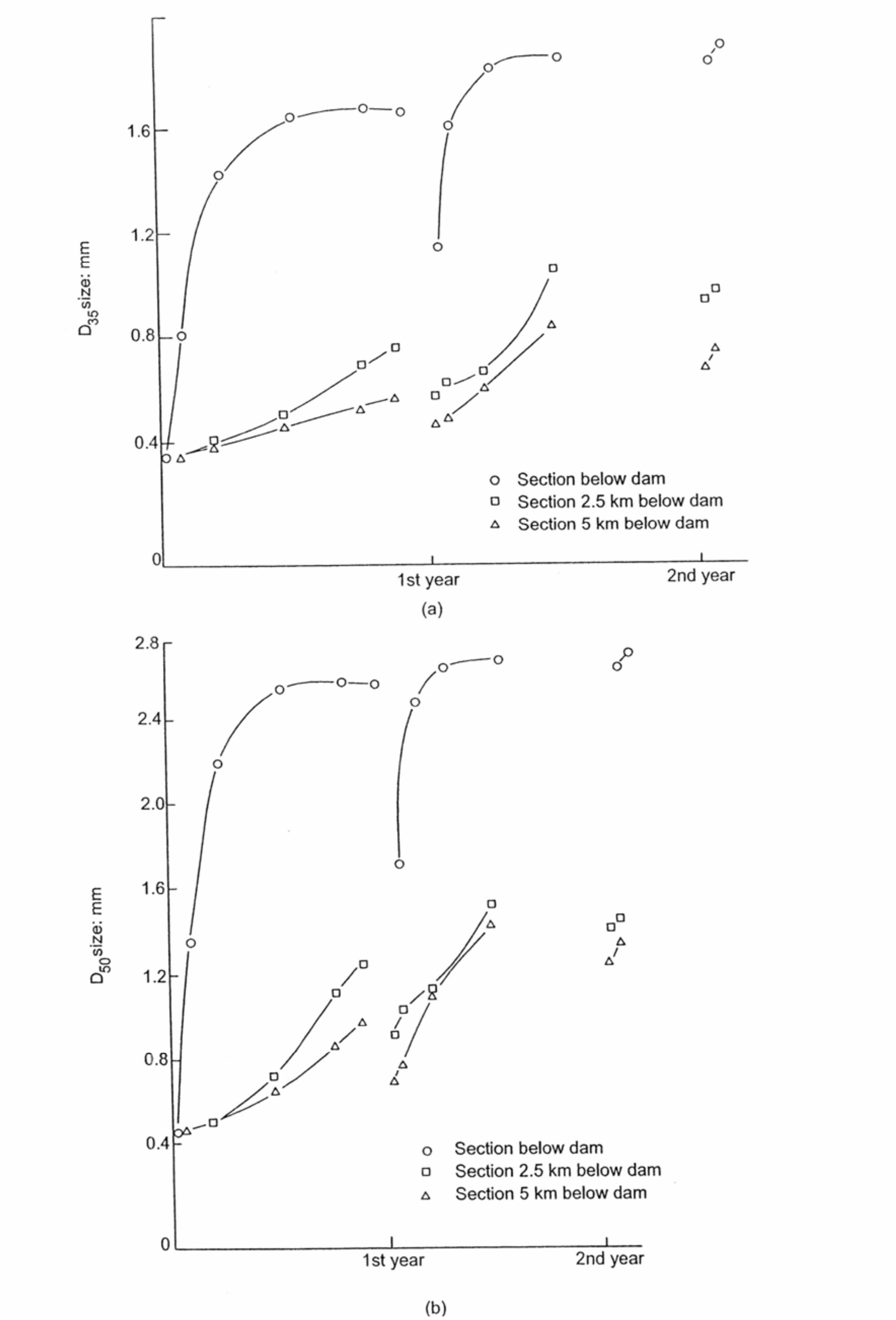
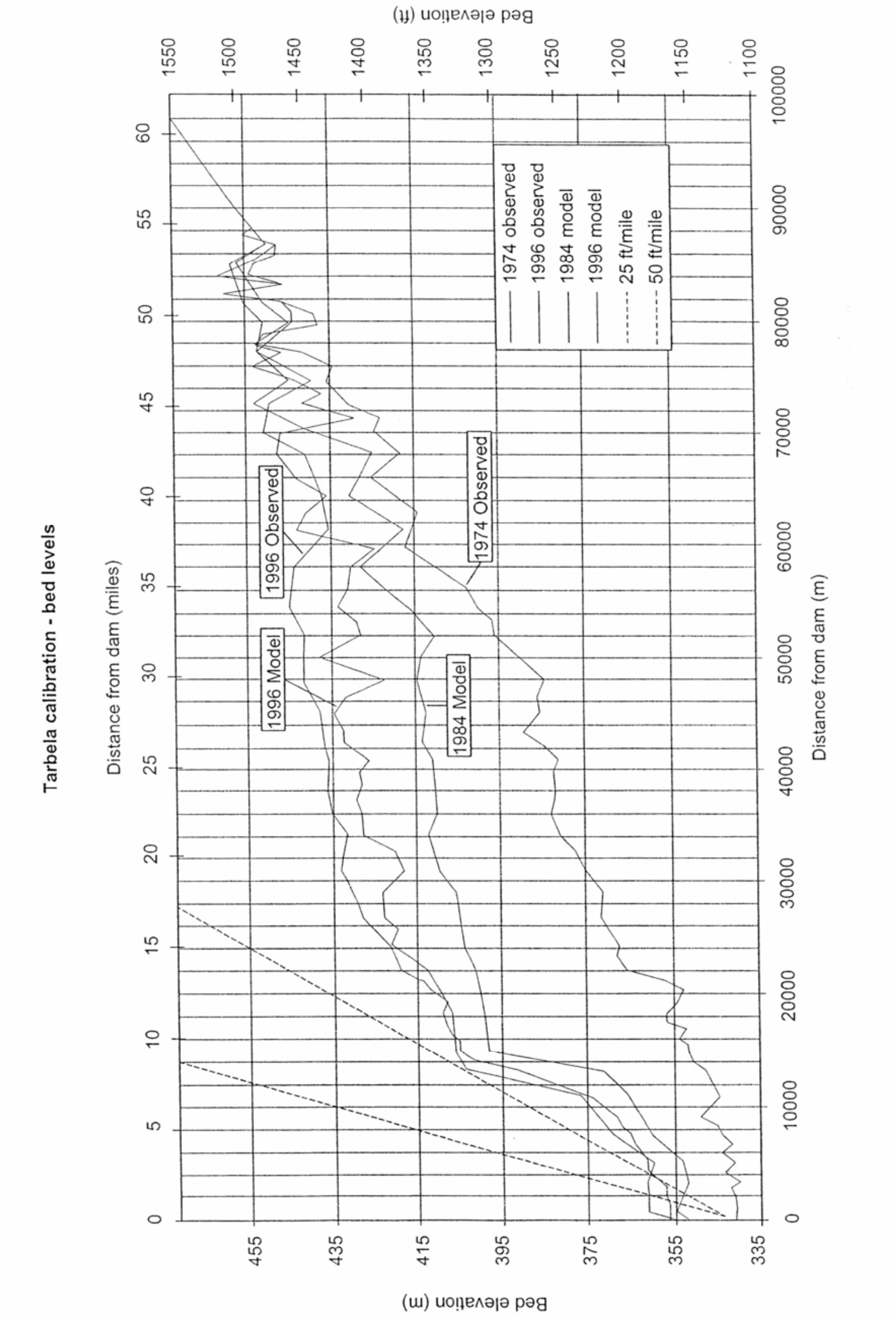


Figure 11.3 Longitudinal profile of bed levels in Tarbela reservoir with and without sediment flushing



Two and three dimensional models can produce similar information to that produced by one-dimensional models but on a two or three dimensional grid. Thus greater spatial resolution of the information is available. In addition they can produce information on the variation of flow and sediment parameters in the extra dimension or dimensions.

Two and three dimensional numerical models have been used to simulate:

- flow and sediment movement around an intake structure,
- flow and scour around a bridge pier
- flow and sediment movement in flushing sediment from a reservoir.

This type of modelling is still currently the preserve of specialists and it is suggested that expert advice is sought before embarking on such a study.

<u>Kapunga intake</u>

Figure 11.4 shows the layout of Kapunga intake with an intake to an irrigation scheme on the left bank. The interest is to be able to predict and, if possible reduce, the amount of sediment that enters the intake. A three-dimensional flow model was used to study sediment movement in the neighbourhood of the intake. Figure 11.5 shows the surface and near bed flow velocities while Figure 11.6 shows the corresponding streamlines. The flow velocities and stream lines indicate that the intake is preferentially taking flow from the higher levels in the flow. The performance of the intake had also been modelled using a physical model. Due to scaling effects in the model a higher proportion of the sediment load was taking place as bed load than in the prototype. As the bed load is concentrated near the bed and as the intake was abstracting predominantly surface water the physical model predicted that little sediment would enter the intake. In the numerical model the sediment could be represented without any scale effects and so the behaviour of the sediment in the neighbourhood of the intake could be truly represented. This indicated that more sediment would enter the intake than was indicated by the physical model. This was confirmed by observed measurements when the scheme was built. Figure 11.7 shows the performance of a number of intakes. The performance ratio is a measure of how effective the intake is at excluding sediment. If then the water entering the intake has the same sediment concentration as that in the river then the Performance ratio is 0, while if no sediment enters the intake then the performance ratio is 1. This figure shows that physical models can be poor in representing the behaviour of fine sediments while numerical models can simulate their behaviour more successfully.

Figure 11.4 Layout of Kapunga intake

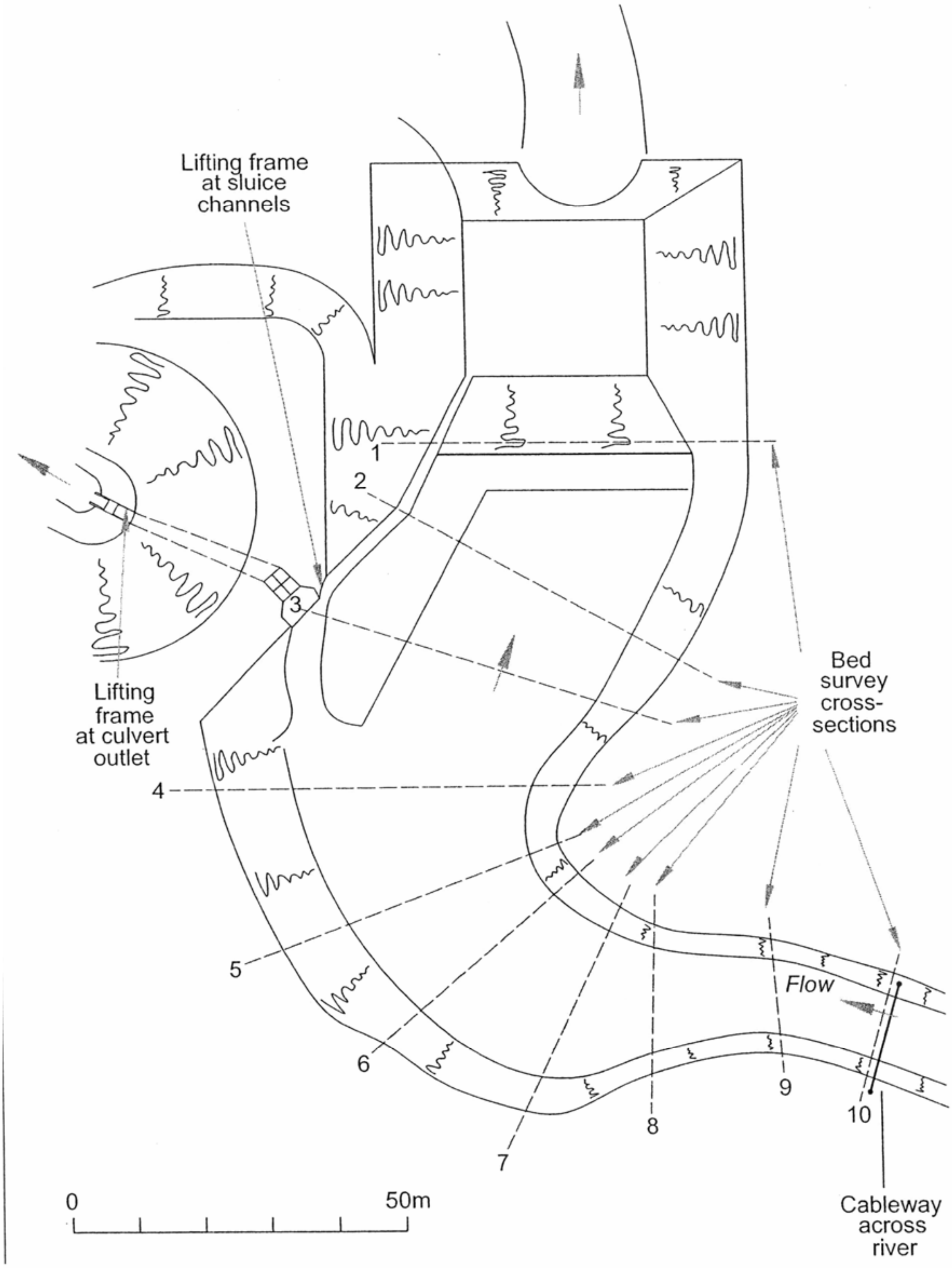
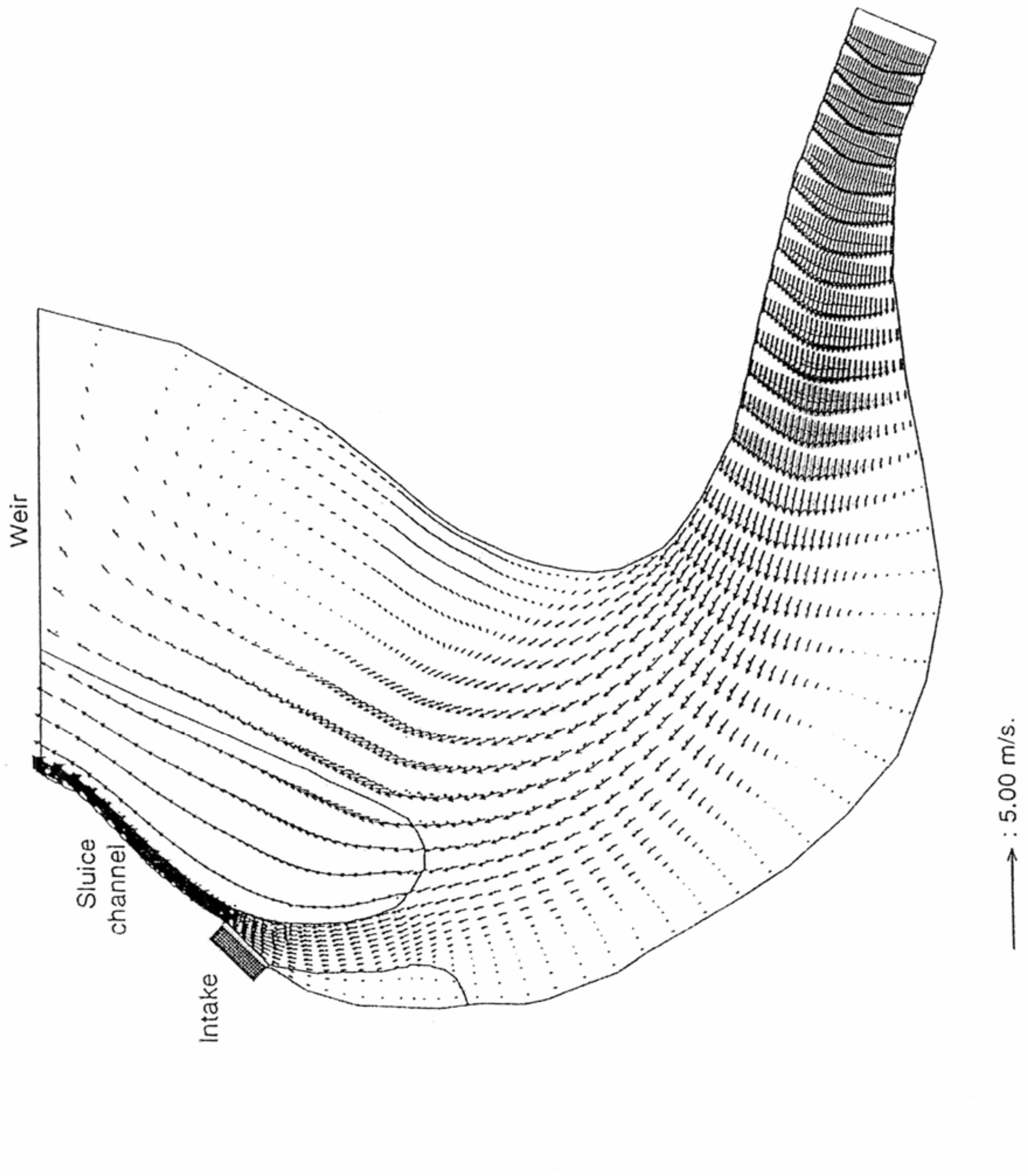


Figure 11.5 Kapunga intake: surface and near bed flow velocities



Flow vectors at the surface are shown as full lines, flow vectors at the bed as dotted lines

Figure 11.6 Kapunga intake: streamlines

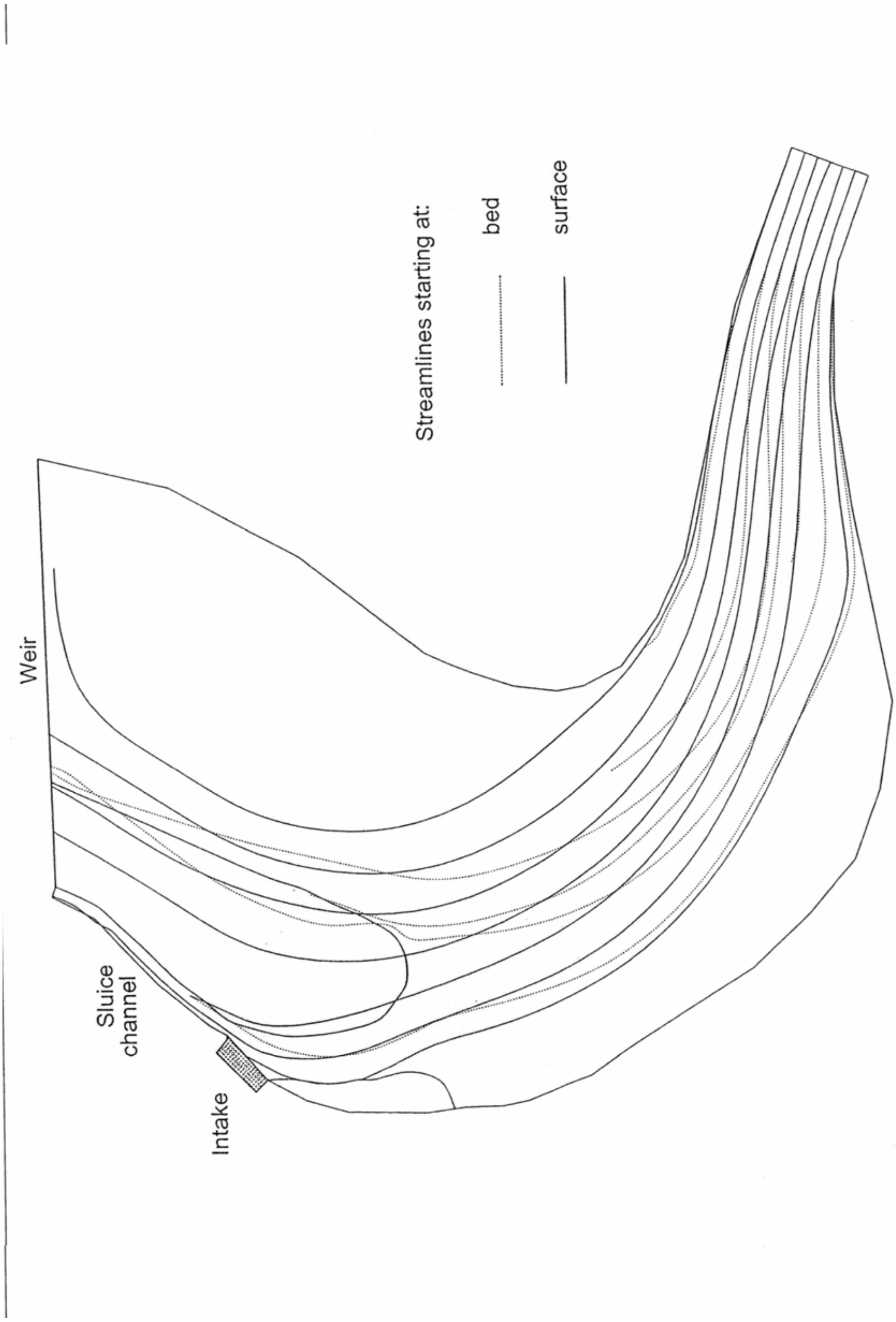
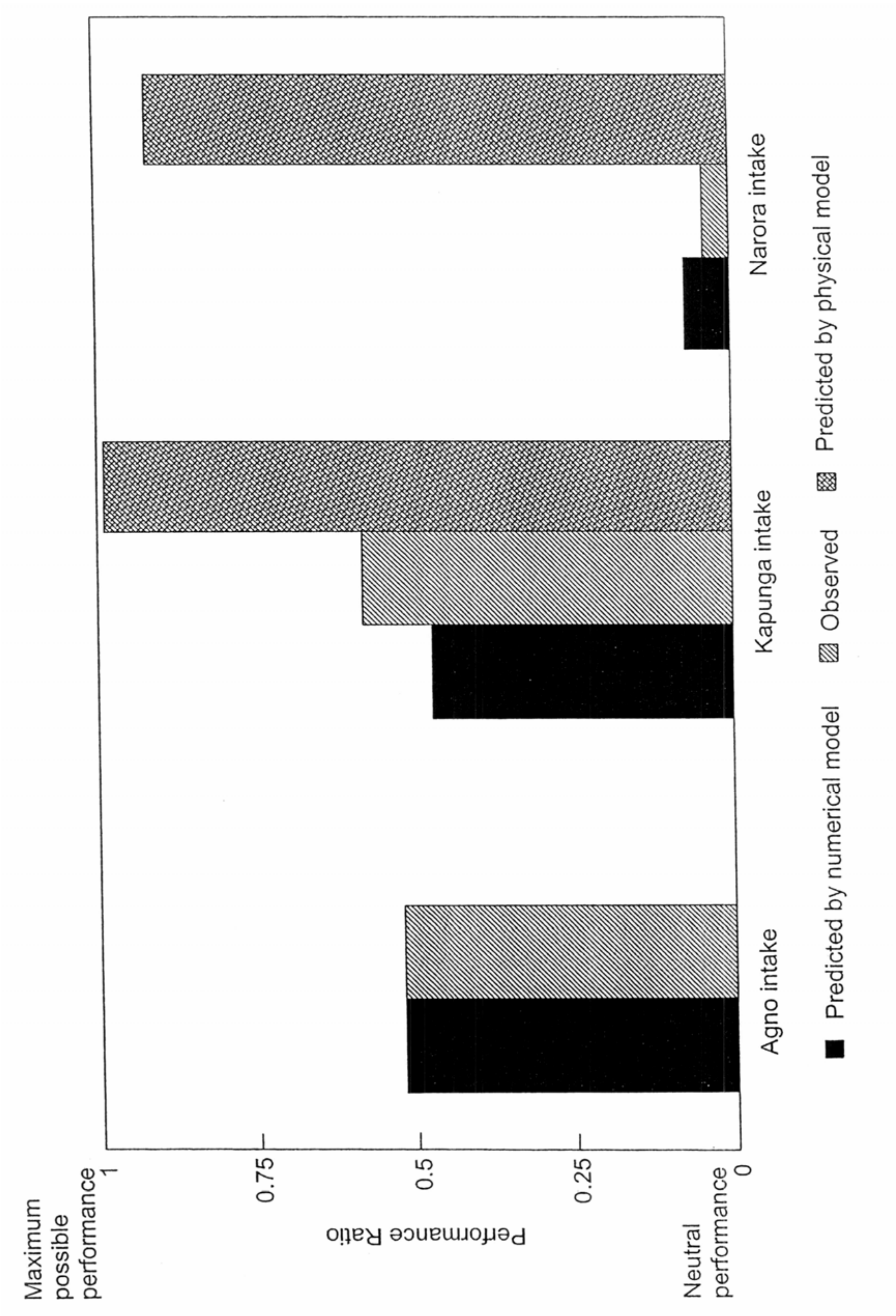


Figure 11.7 Kapunga intake: performance of intake



11.3.4 Physical models

Sediment problems can also be investigated using physical models, which can be attractive tools as they are capable of simulating:

- initiation of motion,
- alluvial resistance,
- sediment transport and
- channel plan form and shape.

Limitations in our understanding of the physical processes involved in sediment movement hamper the development and application of numerical models but, providing physical models have been designed and scaled appropriately, they do not suffer from this problem. Just as there is a range of different numerical models to look at a range of different types of problems so one can design physical models to reproduce different aspects of sediment physics. To reproduce all aspects of sediment movement, including initiation of motion, type of sediment movement, alluvial friction and sediment concentration requires a model scale of 1to 1. As a result any mobile-bed physical model requires a compromise and involves some scale effects with the precise compromise that is adopted depending upon the dominant processes that need to be reproduced for a particular application.

Physical models have been used to investigate:

- the impact of river training works,
- the location and operation of an intake on a river and its impact on river morphology,
- investigating the sediment problems associated with a barrage,
- local scour at structures.

Physical models can have all of the bed mobile, to represent the overall sediment dynamics, or, for local problems such as local scour, only the relevant part of the bed may be mobile and the rest can be fixed.

To accurately reproduce the sediment phenomena the model scale normally needs to be quite large which normally constrains the overall length of channel that can be simulated to a few kilometres at most. The model sediment has to be scaled down from the prototype. This can create problems if the prototype sediment is non-cohesive but the correspondingly scaled model sediment would then begin to exhibit cohesive characteristics. To avoid this light-weight sediments with densities less than that in the prototype are sometimes used. Even using light-weight sediments it can be difficult to simulate the movement of fine sediments in physical models without introducing significant scale effects. In such cases it may be preferable to use two or three-dimensional numerical models instead.

Mobile bed sediment modelling is only carried out by a few specialist hydraulic laboratories and it is recommended that expert advice is sought before embarking on such a study.

Example: Modelling a proposed intake on the Sabi River, Zimbabwe

An intake to abstract 12.5 m^3/s was proposed on the Sabi River in Zimbawe. In the area of the proposed intake the mean overall width of the river is 320 m though the width may vary from 200 to 1,000 m.. The bed sediment consists of a sand with a D_{50} size of approximately 1 mm. The mean annual flood in the area is 1,250 m^3/s. A study was required to:

- check that the proposed site for the intake was acceptable,
- investigate engineering works which might be necessary to ensure that water is always available at the intake,
- to advise on operational rules for the intake throughout the annual flow sequence

The model was designed to reproduce the overall regime conditions in the river. Thus calculations were carried out to confirm that the present river was in regime. The same regime equations were then used to define the dimensions of the model that would also be in regime and to specify the scale relationships. The resulting scale relationships were (λ_p represents the ratio of the model to the prototype value for property p):

a) Geometry

Depth,	λ_d = 1:20	(Vertical scale)
Width	λb = 1:120	(Horizontal scale)
Bed slope	λS_0 = 5.5:1	

b) Water flow

Discharge	λ_Q = 1:5,000
Velocity	λ_V = 1:2.25
Froude number,	λ_{Fr} = 2.0:1
Time	λ_T = 53:1

c) Sediment

Discharge	λ_{QS} = 1:1,000
Volumetric	λ_{Vol} = 1:288,000
Morphological time	$\lambda_m = \lambda_{QS}/\lambda_{Vol}$ = 288:1

It should be noted that in order to reproduce the overall regime of the river it was necessary to use different horizontal and vertical scales and that Froude number similarity was violated. The model appeared to reproduce very well the overall regime behaviour of the river (White, 1982).

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