A Review of Current Knowledge

SEDIMENTS IN THE FRESHWATER ENVIRONMENT

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Review of Current Knowledge

This review is one of a series of Reviews Of Current Knowledge (ROCKs) produced by FWR. They focus on topics related to water supply, wastewater disposal and water environments, which may be the subject of debate and inquiry. The objective of each review is to produce concise, independent scientific and technical information on the subject to facilitate a wider understanding of the issues involved and to promote informed opinion about them.

Cover

The Dharan to Dhankuta road crossing the Sapt Koshi, Nepal

Review of Current Knowledge

Sediments in the Freshwater Environment

Coarse sediments in the Leoti Khola, Nepal

Author: Dr W R White

Review of Current Knowledge

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1 Introduction

This review of current knowledge (ROCK) is concerned with the movement of sediments in the freshwater environment, an important subject but a very complex one. The ROCK provides an outline of the subject and a description of some of the principles used in the analysis of the many complex processes. However, for details of the analytical methods it is necessary to consult major text books on the subject.

Erosion of the earth's surface by water, wind and ice has occurred over geological time scales. Sediments released in this way undergo successive periods of deposition and re-erosion as the landscape changes.

In the distant past the processes of erosion and deposition were natural phenomena which were largely unaffected by man. However in the last millennium there have been significant changes caused by the activities of man and these changes have intensified since the start of the industrial revolution. The rapid growth in population together with changes in land use practices for industry, housing and agriculture mean that man now has a significant influence on the movement of sediments.

A knowledge of the complete cycle of detachment, entrainment, transportation, deposition and consolidation of sediments provides an understanding of how sediments move through the landscape. It also provides a means of predicting future changes as affected by the activities of man. An example of the latter would be in the construction of new water supply reservoirs. How quickly will they lose capacity due to sedimentation? What can be done to extend their useful life?

In Chapter 2 typical sediment related problems are described in general terms.

Chapter 3 gives details of the types of sediment and their characteristics. Coarse sediments are moved by water in a very different manner from fine cohesive sediments.

The subject of soil erosion from catchments is discussed in Chapter 4 including estimates of worldwide erosion rates and the means by which these rates may be minimised.

Chapter 5 describes the movement of sediments in rivers and reservoirs.

Chapter 6 outlines some of the predictive techniques used to analyse sedimentation problems. Details of these techniques are too complex to be covered in detail.

The Appendix gives a list of British and International Standards which relate to sediments and sediment movement.

2 Sediment related problems

2.1 Local scour

Local scour can be defined as the degradation of river banks and/or river beds. The scour can be caused by:

- changes in channel alignments when the flow meets in-erodible banks,
- changes in local flow patterns caused by man-made structures such as bridges,
- energy dissipation when water flows over weirs or spillway structures.

Local scour is often caused by man-made structures and it is important to understand the mechanics of the process in order to design safety and stability into future infrastructure such as road and rail bridges.

Two types of local scour are often quoted; clear-water scour where there is no significant input of sediment to the area and live-bed scour where the scouring flow carries a significant sediment load. Clear water scour is the more aggressive form and can result in more damaging local erosion.

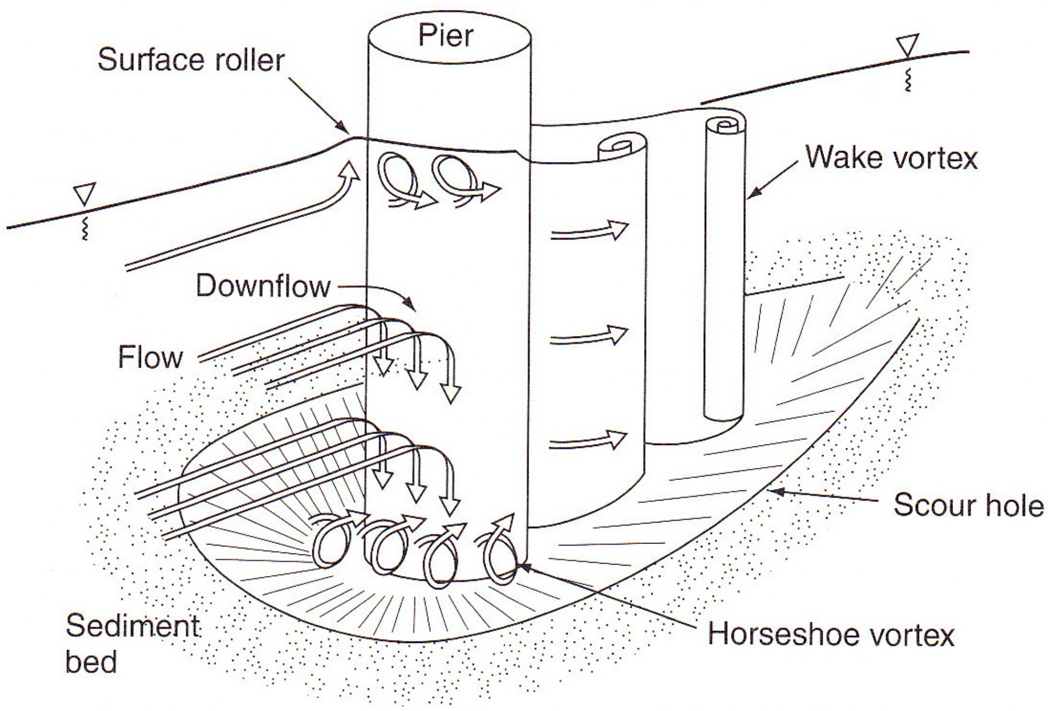

Figure 1 **Flow patterns and scour around a circular bridge pier**
Source: **Hamill L (1999)**

Figure 2 Bridge pier failure caused by local scour, Workington, UK
Source. www.nce.co.uk

2.2 Meandering and braiding in rivers

River channel patterns are varied. Some channels run virtually straight, some exhibit meandering patterns within the width of the valley and some break into multiple channels and become braided. Meandering channels are particularly unstable and progressive erosion and deposition tends to cause the meanders to migrate downstream. This movement of the river channels often endangers adjacent man-made infrastructure.

Experiments have shown that, for a given steady flow of water and a given bed material size and load, the alluvial channel will develop specific cross-sectional dimensions and a specific longitudinal slope. This is known as the equilibrium slope and was shown by ***White W R, Bettess R and Paris E (1982)*** to be such that the channel achieved maximum sediment transporting capacity. With this in mind ***Bettess R and White W R (1983)*** carried out experiments in a large scale flume facility at HR Wallingford in which the flume could be tilted to produce variations in longitudinal "valley" slope. The flume was initially set to the equilibrium slope and, as predicted, a straight alluvial channel developed down the middle of the broad flume facility. The flume was then set progressively to a series of steeper slopes and the channel patterns were observed. As the slope was increased meandering developed with ever increasing sinuosity until a point was reached when several channels developed and a braided pattern emerged. Details are given in Chapter 6.

There are obvious differences between conditions in the laboratory and those that occur in nature, the main one being that rivers are subject to variations in flow whereas laboratory work is generally carried out with steady flows. A second difference is that sediments in natural channels often exhibit a range of sediment sizes whereas work in the laboratory is mainly carried out with a near-uniform sediment size. This makes interpretation of laboratory results difficult but the general reasons for meandering and braiding are clear. Rivers will develop meanders when the valley slope exceeds their equilibrium slope and if this discrepancy becomes too large rivers will split into several channels and become braided.

Figure 3 **A meandering tributary of the Amazon**
Source: **W R White**

Figure 4 A braided channel, Waimakariri, New Zealand
Source: W R White

2.3 Sediment deposition and erosion in reservoirs

There are around 45 000 large reservoirs worldwide used for water supply, power generation and flood control. See ***ICOLD (1998), Morris L M and Fan J (1997)*** and ***Palmieri A, Shah F and Dinar A (1998).*** Between a half and one percent of the total storage volume is lost annually as a result of sedimentation and 300 to 400 new dams would need to be constructed annually just to maintain current total storage. However, increasing populations and increasing consumption per capita mean that the demand for storage is rising inexorably despite the increasing use of alternative sources and the more efficient use of water. The introduction of flushing facilities in some old dams, where appropriate, and the inclusion of such facilities in the design of new dams could help to minimise this need for additional storage.

The benefits attributable to dams and reservoirs, most of which have been built since 1950, are considerable and stored water in reservoirs has improved the quality of life worldwide. These benefits can be classified under three main headings:-

- *Irrigation:* About 20% of cultivated land worldwide is irrigated, some 300 million hectares. This irrigated land produces about 33% of the worldwide food supply. Irrigation accounts for about 75% of the world water consumption, far outweighing the domestic and industrial consumption of water.
- *Hydropower:* About 20% of the worldwide generation of electricity is attributable to hydroelectric schemes. This equates to about 7% of worldwide energy usage.
- *Flood control and storage:* Many dams have been built with flood control and storage as the main motivator. The Hoover dam, the Tennessee Valley dams and some of the more recent dams in China fit into this category.

In many areas of the world the life span of reservoirs is determined by the rate of sedimentation which gradually reduces storage capacity and eventually destroys the ability to provide water and power. Many major reservoirs are approaching this stage in their life.

There are many ways of preserving reservoir storage but the techniques are only effective under certain favourable conditions and are not universally applicable. The alternative is to build more dams to replace the depleting storage of the existing stock. However, there are fewer and fewer good dam sites available and new dams can have serious environmental and social consequences.

Two common methods of removing sediments from reservoirs are:

- draining the reservoir and removing sediments mechanically,
- flushing sediments through low level outlets in the dam wall.

Both methods can result in wastage of water required for irrigation and loss of generating capacity at hydroelectric power schemes. The subject of flushing sediments from reservoirs is covered in more detail in ***White W R (2001)***.

Figure 5 **Flushing reservoir sediments through low level outlets, Tarbela, Pakistan**
Source: **W R White**

Figure 6 **Reservoir sediment deposits, Zimbabwe**
Source: **W R White**

3 Sediment characteristics

A useful framework for categorising sediments is to consider how the various sizes are transported by flowing water. Very fine cohesive sediments remain in suspension for long periods even in still water areas such as ponds and lakes. Somewhat larger particle sizes may not exhibit cohesive properties but they travel almost exclusively in suspension when found in an alluvial stream. Large particles travel either by rolling along the bed of the stream or by a series of hops close to the bed. This process is called saltation. In between fine and coarse sediments there is a range of transitional sizes and the nature of their transport depends on local flow conditions.

Ackers P and White W R (1973) defined the boundaries between these sediment sizes in terms of a non-dimensional term D_{gr} (see reference for details). The definition, in terms of this non-dimensional term, enables the characteristic sizes of materials of differing specific gravities, such as coal or plastic, to be specified. The method showed that coarse sediments travelling in close contact with the bed could be defined, for naturally occurring sands and gravels, as particles greater than 2.5mm in size. Fine sediments, travelling mainly in suspension, were within the size range 0.04mm to 2.5mm. Particles less that 0.04mm in size were found to be mainly cohesive and to travel in suspension in quantities defined more by sediment supply than the local hydraulic conditions.

In nature the situation becomes more complex and a mixture of sediment sizes is often found in one location. This is particularly noticeable in steep mountain rivers where the sediments range from fine particles up to coarse gravels and boulders. The fine particles are often hidden beneath the coarse particles of these rivers, a process known as armouring of the bed. Figure 7 illustrates the effect.

Figure 7 **Bed material underlying an armouring layer, Colorado, USA**
Source: **UNESCO (1982)**

4 Soil erosion and sediment yields

The estimates derived from more than a dozen studies of global average rates of denudation have ranged from 0.06 mm/year to 0.16 mm/year, ***Morris L M and Fan J (1997)***. This is equivalent to estimates of up to 20 x 10^9 t/km^2/year, ***Walling D E and Webb B W (1996)***. Areas with sediment yield over 1 000 t/km^2/year form 8.8% of the total land area and account for 69% of the total sediment yield. Regions with less than 50 t/km^2/year account for about half of the land area and 2.1% of the sediment yield.

4.1 Erosion rates across the globe

A number of estimates have been made of the worldwide distribution of sediment yields. Results from one such study, ***Mahmood K (1987)***, is presented in Table 1.

<table>
<tr><th rowspan="2">Area</th><th colspan="2">Annual Precipitation</th><th rowspan="2">(%)</th><th rowspan="2">Annual Runoff
(km^3)</th><th rowspan="2">(%)</th><th rowspan="2">Annual loss of Sediment (Mt)</th><th rowspan="2">(%)</th><th rowspan="2">Annual Sediment Yield (t/km^2)</th></tr>
<tr><th>(mm)</th><th>(km^3)</th></tr>
<tr><td>N.America</td><td>756</td><td>15.8</td><td>15.4</td><td>6.6</td><td>17.1</td><td>1 460</td><td>10.9</td><td>84</td></tr>
<tr><td>Asia</td><td>740</td><td>25.7</td><td>25.0</td><td>10.8</td><td>28.0</td><td>6 350</td><td>47.4</td><td>380</td></tr>
<tr><td>Africa</td><td>740</td><td>19.7</td><td>19.2</td><td>4.2</td><td>10.9</td><td>530</td><td>3.9</td><td>35</td></tr>
<tr><td>S.America</td><td>1 600</td><td>27.0</td><td>26.2</td><td>11.8</td><td>30.5</td><td>1 790</td><td>13.3</td><td>97</td></tr>
<tr><td>Europe</td><td>790</td><td>7.5</td><td>7.3</td><td>2.7</td><td>7.0</td><td>230</td><td>1.7</td><td>50</td></tr>
<tr><td>Australia</td><td rowspan="2">791</td><td rowspan="2">7.1</td><td rowspan="2">6.9</td><td rowspan="2">2.5</td><td rowspan="2">6.5</td><td>60</td><td>0.4</td><td>28</td></tr>
<tr><td>Oceania</td><td>3 000</td><td>22.4</td><td>1 000</td></tr>
<tr><td>**Total**</td><td></td><td>102.8</td><td>100.0</td><td>38.6</td><td>100.0</td><td>13 420</td><td>100.0</td><td>165</td></tr>
</table>

Table 1 Worldwide variations in sediment yield

Sediment yield in Asia is four times larger than in South America even though South America experiences the highest rates of runoff in the world. The sediment yield for basins in Asia is over twice the world average and contributes approximately 80% of the world sediment total, ***Jolly J P (1982)***. The largest sediment yields occur in Oceania and locally they are often well above the average figure of 1 000t/km^2/year.

A global perspective of sediment yields is shown in Figure 8, ***White W R (2001)***.

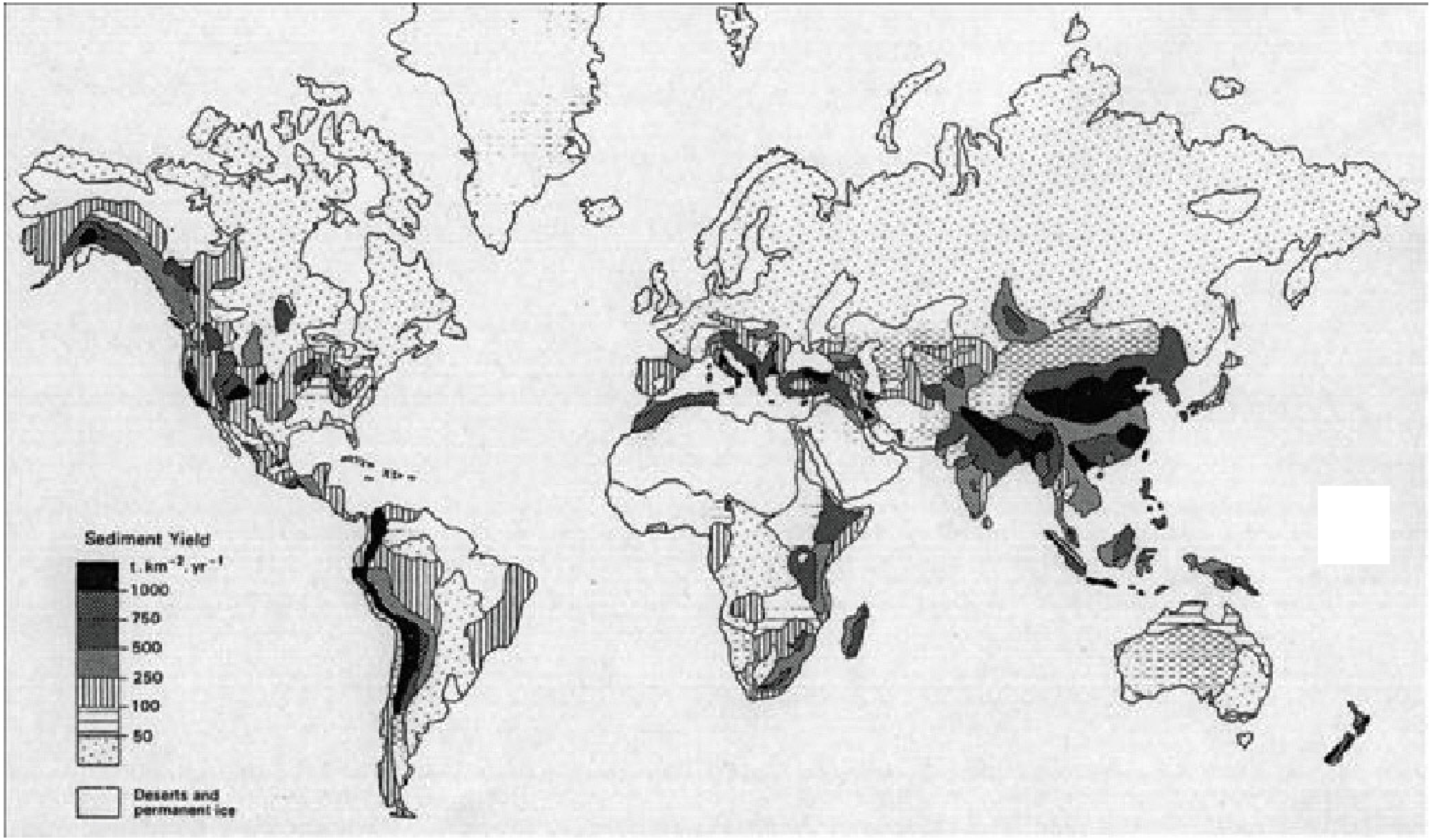

Figure 8 **Worldwide variations in sediment yield**
Source: **White W R (2001)**

4.2 Areas of high erosion rates

Further comments by various researchers on areas where particularly heavy erosion occurs are given below:

Significant and extensive areas of high erosion include mountainous areas, such as the Andes, the Himalayas, the Karakorams, the Rockies and the mountains of East Africa. Areas with volcanic soils such as Java, the South Island of New Zealand, Papua New Guinea and parts of Central America also exhibit very high erosion rates, ***Morris L M and Fan J (1997)***.

The most intensive local rates of erosion are to be found in China, Taiwan, the Philippines, Indonesia, Java, Kenya, New Guinea and New Zealand, ***Walling D E and Webb B W (1983)***. The reasons are associated with active tectonics and volcanism, steep slopes, high precipitation amounts and intensities, high and irregular runoff, dissected mountain relief composed mainly of sedimentary rocks and human influence by agriculture and logging, ***Dedkov A P and Moszherin V I (1992)***.

Taiwan discharges more sediment to the ocean per unit area than any other country in the world. Streams draining the central range record suspended sediment yields of 13 760 t/km^2/year. One small basin exports 31 700 t/km^2/year. The sediment discharge of Taiwan is nearly five times larger than that from the continent of Australia, even though it is 210 times smaller, ***Walling D E and Webb B W (1983)***. In New Zealand recorded values reach up to 28 000 t/km^2/year with a mean value of around 2 000 t/km^2/year. The highest recorded specific sediment yield is 53 500 t/km^2/year for the Huangfuachan River with a catchment area 3 200 km^2. This river is a tributary of the Yellow River in China, ***Walling D E and Webb B W (1983)***.

4.3 Areas of low erosion rates

Global minima below 2 t/km^2/year have been documented. These areas of low sediment yield are usually relatively flat and arid with inadequate stream flow to transport large sediment volumes. The arctic regions with low relief, little precipitation and little human impact were identified in this category by ***Morris L M and Fan J (1997)***. Areas with low mountains in temperate zones were identified by ***Dedkov A P and Moszherin V I (1992)***. These areas include Scandinavia, the Urals, the mountains of South Siberia and the Trans-Baikal region,

4.4 Control of soil erosion

The control of soil erosion is the practice of preventing or controlling the loss of soil from specific areas. Typical concerns are for areas used for agriculture and land development. There are also concerns, on a more local basis, for soil loss during major construction works. River bank erosion is also a cause of soil loss.

The development of techniques for minimising soil loss are important for several reasons:

- loss of fertile soil in agricultural areas diminishes agricultural yields,
- loss of soil affects wildlife habitats,
- loss of soil in urban areas can affect stormwater run-off management,
- loss of soil during construction can cause water quality problems.

The methods used to minimise soil loss are varied and numerous. They differ according to the nature and size of the area to be protected.

In large catchments, particularly in remote mountainous areas, check dams are often built on the smaller tributaries to minimise the movement of sediment downstream. This procedure does not retain soil on the land but this is rarely required in mountainous areas. It does, however, protect water storage reservoirs further downstream from excessive siltation.

On a more modest scale, usually in flatter agricultural areas, the methods used are numerous:

- careful crop rotation,
- contour bunding and ploughing,
- reforestation,
- strip farming,
- storage ponds at the outlet from the area.

Construction sites are usually much smaller in area and erosion control is only required for the period of the construction works. Methods used include:

- temporary mats of fibre or steel to protect the surfaces,
- drainage channels and storage ponds to collect any eroded material.

5 Sediment movement in rivers and reservoirs

5.1 Total bed material load

The transport of non-cohesive sediments by a steady uniform flow of water in an open channel is a complex process, and the physics of this two-phase motion is of ongoing research interest. Many theories have been put forward to provide a satisfactory framework for the analysis of sediment transport data, some being based on the physics of particle motion and others on similarity principles or dimensional arguments. Very different answers may result from the use of published predictive equations and some are complicated to apply.

There has been an academic preference for shear stress to be considered as the main parameter defining the stream's transporting power. However, the total shear on a deformed bed which may have ripples or dunes is in part composed of the along-stream components of the normal pressures on the irregular bed profile. Although these normal pressures may contribute indirectly to sediment motion through suspension, many methods separate the bed shear into the non-transporting form loss and the shear on the grains. As the rate of transport is very sensitive to transporting power, inaccuracy in this separation procedure may give large errors of prediction. In engineering practice, this factor is important because few natural streams have a plain bed. Several researchers have suggested that shear stress is not the most convenient, nor the most rational basis of a sediment transport function, and have proposed methods of correlation that use average stream velocity in preference to shear stress.

Ackers P and White W R (1973) suggested a framework for the transport of non-cohesive sediments which:

- could be used pragmatically for engineering studies,
- took into account the differences between the finer sediments which travel mainly in suspension and the coarser sediments which travel mainly by rolling or saltating along the bed of the channel,
- was non-dimensional and could therefore be used in any system of units and
- was dimensionally consistent.

The method proposed was validated on an extremely wide range of laboratory sand transport data. It was then tested against field data and some further laboratory data where lightweight sediments such as bakelite or coal had been used. The method is quoted in many text books and because of its general nature is used in many mathematical models for the evaluation of sediment transport rates.

Many other theories and methods have been produced, mostly for very specific applications and based on restricted sets of data, see ***Raudkivi A J (1998)***.

Initial motion conditions

Engineers often wish to know whether sediment in a particular channel will move under certain hydraulic conditions. Lack of movement points to the existence of a stable channel, movement may lead to changes in channel formations. The "initial motion condition" is the condition when sediment starts to move. This condition cannot be defined precisely as odd bursts of turbulence can move individual particles under any hydraulic condition. The method used to estimate initial motion conditions is to look at sediment transport data over a wide range of flows and to establish statistically when "zero transport" occurs.

5.2 Suspended fine material load

In rivers the suspended sediment load can comprise sand sizes plus silts and clays. The sand sizes are kept in suspension by the turbulence of the flow and the amount of sand in suspension varies with river flow. At low flows there is little sand in suspension but during flood flows there may be significant quantities in suspension. On the other hand the turbulence required to keep silts and clays, the fine material load, in suspension is very low and they remain in suspension over a wide range of flows. This means that the flow is not saturated and the quantity of fine material in transport is usually governed more by the supply of material from the catchment than the transporting capacity of the flow. Figure 9 shows an example of a high suspended load in the Yellow River, China.

The suspended fine material load in rivers is usually derived from field measurements. In the lower reaches of rivers the movement of fine sediments involves complex calculations which take into account the fall velocity of the fine particles and the shear stress required to erode deposited and sometimes compacted beds of clay and silt, see ***Raudkivi A J (1998)***.

Figure 9 **Fine suspended sediments, Yellow River, China**
Source: **www.tripadvisor.com**

6 Predictive techniques for sediment movement

6.1 Data collection and analysis

Data collection

The analysis of sedimentation problems in river basins is a major undertaking and all analysis techniques depend upon the acquisition of field data. Dependent upon the size and nature of the project being undertaken any or all of the following data may be required:

Hydrological data

- rainfall data including the average annual precipitation, the intensity of the rainfall and the seasonal distribution,
- runoff data including daily flows, annual flows and any seasonal variations,
- wind data (in arid zones).

Catchment characteristics

- topographical maps,
- geological maps,
- low altitude photographs,
- remote sensing,
- field testing of soil and/or gully erosion,
- morphological data on historic river movements.

Sediment transport and deposition

- suspended sediment samples taken on a frequency which might vary between a day and a year,
- bed load transport rates over a range of river conditions,
- bed material samples to establish the size range of the bed sediments,
- reservoir surveys to establish sedimentation patterns, delta formation and any degradation downstream of the reservoir,

An example showing the complexity which can be found in bed material samples is shown in Figure 7. This figure shows fine material underlying a coarser armouring layer in the Colorado, USA.

Further information on the acquisition of data is to be found in ***UNESCO (1982).***

<u>Data analysis</u>

The following sections give some details of the analysis techniques used in specific circumstances. However, two general points are worth making:

- Interfluvial areas present a particularly difficult analytical problem because there are so many variables involved such as sheet erosion, gully erosion, changes in vegetative cover etc.. Ongoing research in this area seeks to improve analytical techniques.
- Once sediment has reached the water course we are today in a much improved position to predict its behaviour. The emergence of powerful computing facilities in recent years, together with large scale laboratory experiments, has revolutionised the analysis of the hydrodynamic processes which govern the interaction between water and sediment.

6.2 Estimation of sediment yields from catchments

Sediment yields from catchments are rarely made by making measurements on the land surface although some studies have looked at sediments in small streams adjacent to agricultural land. More commonly, sediment yield is computed from reservoir surveys or from sediment monitoring stations in rivers. Although neither of these methods is free from uncertainties, reservoir survey data generally represent a more reliable measure of the long-term sediment yield from the catchment. However they do not give any information about short term changes which might relate, for example, to particular flood events. Ideally both types of measurements should be made and cross-correlations carried out wherever possible. ***Morris L M and Fan J (1997)*** give more details on this subject.

<u>Reservoir surveys</u>

Reservoir surveys are attractive for the following reasons:

- they only need to be carried out periodically, say once a year,
- they can be carried out safely during low flow periods,
- they are less costly than continuously monitoring river stations,
- bathymetric surveys can be carried out quickly and with high accuracy using modern sonar techniques,

- successive bathymetric surveys provide a measure of the total sediment load from the catchment, at least during the early life of a reservoir when almost all the sediment is trapped within the reservoir.

River monitoring

Sediment transport in rivers cannot be measured directly. It must be computed from simultaneous measurements of river flow and sediment concentration, both of which show very large variations with time. Measurement of river flow is relatively straightforward and can be achieved using a number of methods. These include measurements of the stream velocity and cross-sectional area, the use of flow measurement structures such as weirs and flumes and the use of ultrasonic or electromagnetic methods. The continuous measurement of sediment concentrations is more problematic, particularly where there is a significant quantity of coarse sediment in motion.

Sediment monitoring in rivers often involves:

- depth integrated sampling of sediments travelling in suspension,
- pumped samples taken over a wide range of flow conditions,
- continuous sampling of fine sediments,
- bed load measurements using sediment traps or pits.

6.3 Estimation of sediment loads in rivers

There are many reference books covering sediment loads in rivers, see ***Yalin M S (1972), Graf W H (1984), Garde R J and Ranga Raju K G (1985) and Raudkivi A J (1998)***. These show the many ways in which researchers have approached the subject, taking into account the different factors which affect sediment supply and sediment movement.

There are three specific modes of transport to be considered when evaluating sediment movement in rivers:

- the movement of fine sediments, generally less than 0.04mm sand sizes, which travel almost entirely in suspension,
- the movement of coarser sand sizes which travel along the bed at low flows and in suspension at higher flows,
- the movement of coarse gravels which travel in close contact with the bed at almost all flows.

Where movement is in suspension the trajectory of individual particles is governed by turbulence in the flow and is random in nature. Movement along the bed of a channel is governed more by shear forces on individual particles causing either rolling or brief periods of saltation.

Fine sediments

A practical definition of fine sediments is sand sizes less than 0.04mm. These sizes are often cohesive in nature.

The energy available in the flowing water in rivers far exceeds that required to carry this fine sediment in suspension so the movement of fine sediments cannot be based on the river flow. Instead it must be based on the amounts of sediment entering the river system. In effect rivers are rarely, if ever, "saturated" with fine sediments.

The estimation of fine sediment loads is thus carried out:

- by using established formula which are based upon widespread field observations and which calculate sediment inputs to the river system by considering such factors as the size and nature of the catchment and also the local climatic variables,
- by directly using historic field data for the specific catchment under consideration.

Sediments travelling in suspension

Most sand sizes travel in suspension at medium and high flows. The hydraulic conditions in the river determine if and when a given sediment size will be in suspension.

The introduction of diffusion-dispersion based turbulence models proved to be a major breakthrough in the estimation of suspended sediment loads. Commonly used expressions for evaluating the suspended bed material load are by ***Einstein H A (1950)*** and ***Van Rijn L C (1984)***.

Sediments travelling close to the bed

If the applied shear stress on the bed of a channel caused by the moving water exceeds a threshold value the bed material is set in motion. The most commonly used formula for estimating conditions where sediment movement is initiated was developed by ***Shields A (1936)***. Subsequent movement of sediment in close contact with the bed is often evaluated using the method developed by ***Meyer-Peter E and Müller R (1948)***.

Total bed material load (excluding fine materials)

Because most sand sizes can form either part of the bed load or part of the suspended bed material load, depending on flow, it is convenient to develop methods which take into account both the turbulence issues and the bed shear stress issues. These methods enable the estimation of the total bed material load but do not indicate the separate amounts travelling in suspension or close to the bed.

Commonly used methods of estimating the total bed material load include those of ***Yang C T and Molinas A (1982)*** and ***Ackers P and White W R (1973)***.

Graded sediments

As stated earlier, and shown in Figure 7, natural rivers often exhibit a range of sediment sizes and the question arises as to how the transport rates of the whole mass of sediment are to be derived. In practice the coarser material tends to be in the uppermost layers of the bed and this coarser material shields and inhibits the movement of the finer material beneath. Additionally the finer material underneath the surface layer facilitates the easy movement of the coarse material above. The end result is that the coarser material moves more readily than would be the case with a bed formed entirely of a uniform coarse material of similar size. Conversely the fine material, because of the shielding effect, moves less readily than would be the case with a bed formed entirely of uniform fine material of the same size.

Where the range of sizes is modest it is possible to calculate transport rates using a "significant" sediment size which is often taken as the sieve size through which 35 per cent of the graded bed material will pass. Where there is a very wide range of sediment sizes it is necessary to divide the sample of bed material into a range of discrete sizes. Transport rates are calculated for each size band taking into account the shielding of the fine material and the over-exposure of the coarse material as mentioned above. This subject is discussed in ***White W R and Day T J (1980)***.

6.4 Estimation of local scour in rivers

Local scour in rivers is a complex process. It occurs in regions where there is a discontinuity in the flow pattern or direction. For example local scour occurs on the outside of river bends often accompanied by deposition on the inside of the bend. Scour also occurs where flows meet man-made structures such as smooth concrete side walls or bridge piers set within the main body of flow.

Historically local scour problems have been tackled using physical models of the local area. This is still the best approach where analytical methods are not yet available or are not very precise. Research is ongoing and analytical methods show continuous improvement.

One area which has been studied in detail is the scour which occurs at bridge crossings. There is clearly a financial and environmental benefit in being able to evaluate whether bridges are stable even in the most adverse flood conditions. ***Hamill L (1999)*** gives details of various predictive techniques which are applicable to a range of conditions from clear water scour to live-bed scour, the latter occurring where significant quantities of sediment are in motion and where there is scope for both scour and accretion.

6.5 Estimation of channel characteristics, including meandering and braiding

Rivers exhibit a perplexing range of shapes and sizes and channel patterns vary from straight to meandering to braided. A casual look at mountain rivers shows that they tend to be wide compared with their depth and the sediments tend to be coarse. Further downstream the width to depth ratio decreases and the observed sediments are smaller. Why this should be the case has attracted research over the last century or so. Early work was entirely empirical and was largely qualitative and intuitive. However, an increased database of careful physical experiments in laboratories, a better understanding of the physical processes and the advent of modern computing facilities has, more recently, enabled progress to be made.

Equilibrium channels

Leaving aside the question of meandering and braiding, what determines the stable or equilibrium slope, width and depth of a river channel?

Modern methods to evaluate these parameters use two physical relationships and a variational principle. These are:

- mathematical formulations which describe the sediment movement in the river,

- mathematical formulations which describe the frictional resistance of the bed of the channel as affected by the graininess of the bed sediment and the possible existence of bed features such as ripples and dunes,
- a variational principle which says that the slope, width and depth will develop so that either (a) the sediment transporting capacity is maximised or (b) the channel slope becomes a minimum for the given sediment transporting requirement.

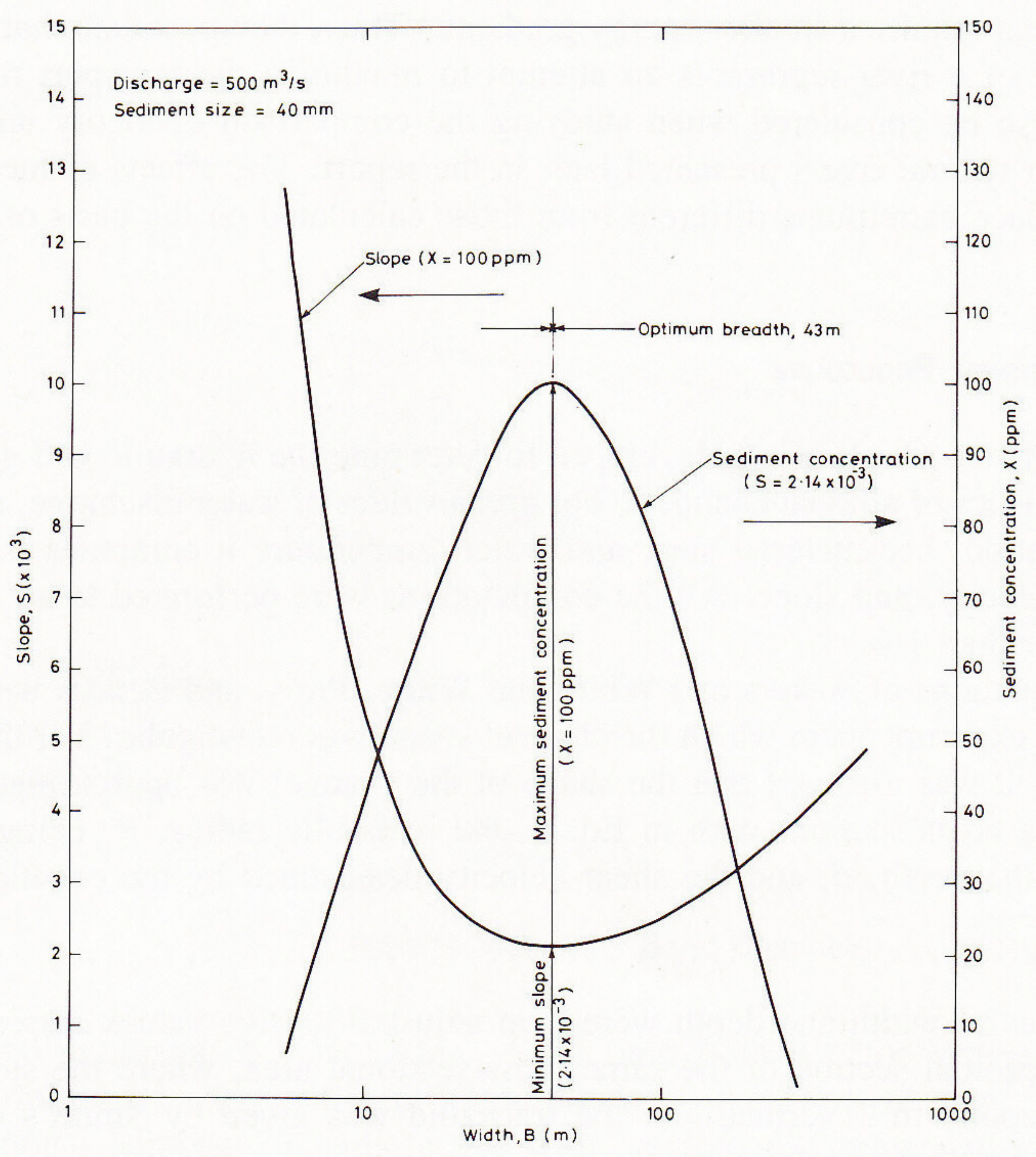

Figure 10 Estimation of river channel parameters
Source : White W R, Bettess R and Paris E (1982)

An example of the computational results using the two variational principles are given in Figure 10. The example assumes a discharge of 500 m^3/s and a sediment size of 40mm. Where a maximum in the sediment concentration exists for a given discharge and slope, it corresponds to the minimum slope for the given discharge and the maximum sediment concentration previously calculated. A full explanation of the methodology together with an appraisal of other methods is given in ***White W R, Bettess R and Paris E (1982)***.

Meandering and braiding

Although the plan shape of rivers displays a continuous variation of form it has traditionally been classified into three broad categories of straight, meandered or braided. The reason why some rivers are straight and others exhibit meandering or braiding remains scientifically unproven but some success has been obtained in exposing one fundamental cause, namely that the equilibrium channel slope, as described above, does not match the slope of the valley in which the river is situated.

The reasons why the valley slope does not necessarily match the equilibrium slope are many:

- tectonic activity which causes the topography of the earth's surface to change over geological time,
- climatic variations over long periods of time,
- continuous erosion and accretion in the catchment,
- capture of tributaries by main rivers etc.,
- man-made interventions such as the construction of barrages and dams.

A useful conceptual model is provided by ***Bettess R and White W R (1983)*** and is shown in Figure 11.

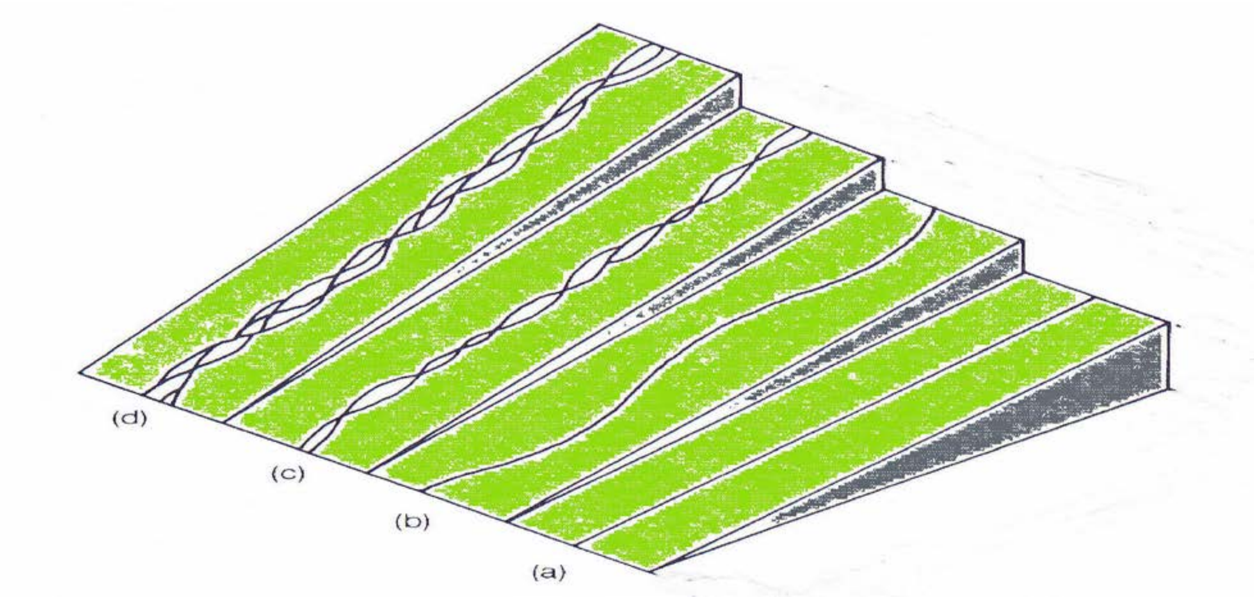

Figure 11 **Theoretical channel patterns**
Source: **W R White**

With reference to Figure 11:

(a) If the valley slope equals the equilibrium river slope then the channel will be straight and in equilibrium.
(b) If the valley slope is greater than the equilibrium river slope then the river can accommodate the discrepancy by meandering. By meandering the river decreases its longitudinal slope because of its increased length and thus attempts to regain its equilibrium value.
(c) and (d) At some critical valley slope the river can no longer achieve its equilibrium slope by meandering because the discrepancy between the equilibrium and valley slopes is too great. The difference between the two slopes must be accommodated in another way and the most common way is for the river to form a braided channel. The river splits into a series of channels each of which, being smaller than the original single thread channel, has a greater equilibrium slope.

In order to test these ideas large tilting flumes have been used to simulate changes in valley slope whilst maintaining the same river flows and sediment loads. The results of one such experiment are shown in Figure 12.

In this laboratory experiment a fixed river flow of 1.0 l/s was used together with a sediment concentration of 200 ppm. Experimental conditions were as follows:

a) the flume, or valley slope, is set to the predicted equilibrium slope and, as expected, the river channel remains straight.
b) the flume slope is set to 1.3 times the predicted equilibrium slope and the development of meanders is clearly visible.
c) the flume slope is set to 1.8 times the equilibrium slope and a braided channel is developed.

a)

b)

c)

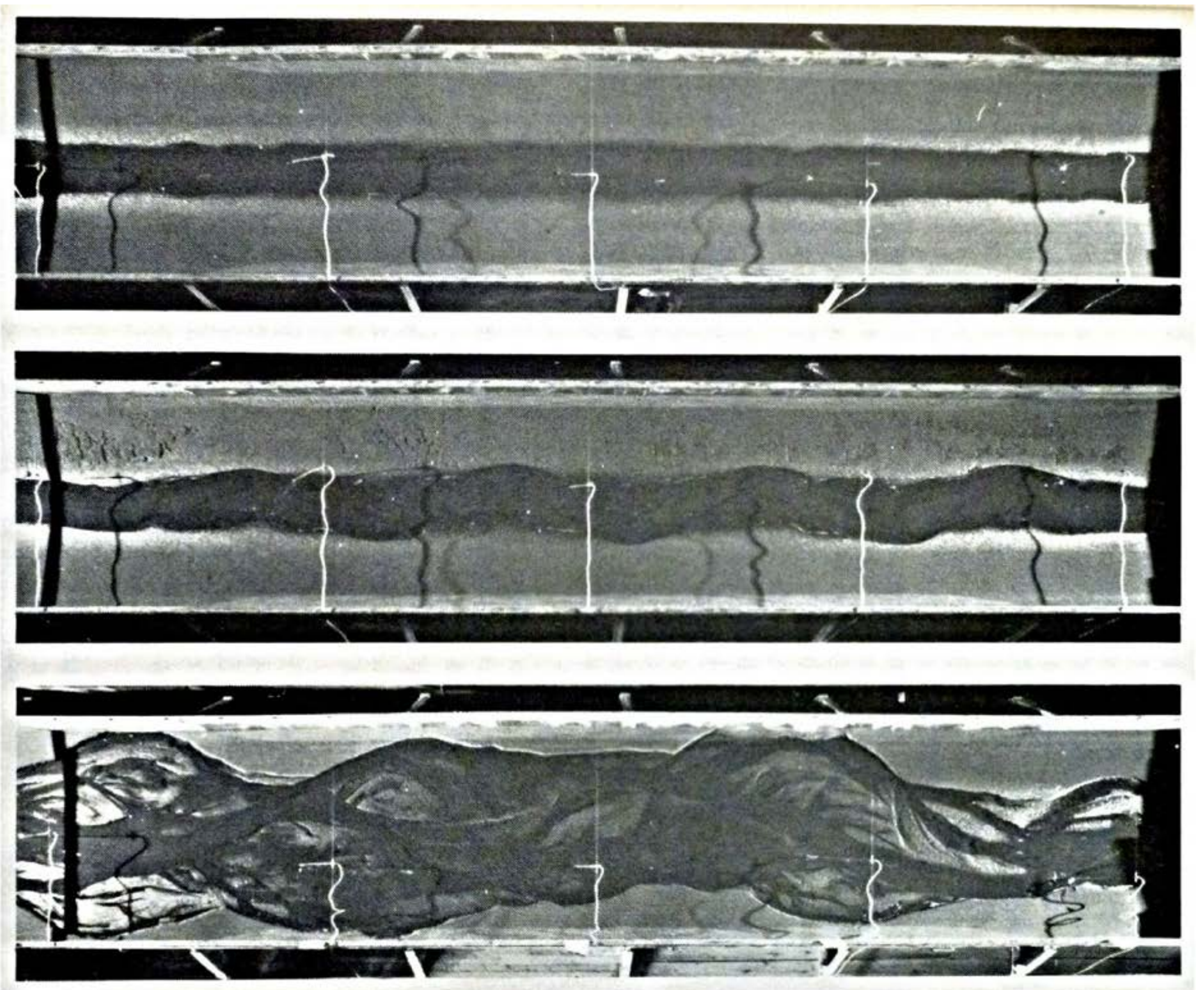

Figure 12 Observed laboratory channel patterns
Source: Bettess R and White W R (1983)

6.6 Estimation of sediment deposition and erosion in reservoirs

Sedimentation and erosion in reservoirs is normally evaluated using numerical (computer based) models. These models are better suited to the task than physical models because of:

- the large size of many reservoirs,

- the wide variation in sediment sizes,
- the lengthy simulations required to evaluate sedimentation over the anticipated life of the reservoir, often 30 to 40 years.

Once a dam is completed it raises water levels and reduces water velocities in the reservoir upstream. This creates a depositional environment within the reservoir. The resulting loss of storage results in a gradual reduction in the regulated yield of the reservoir and this, in turn, results in a reduction in the water available for agriculture and a reduction in the firm energy available from the project.

Additionally there are physical effects of the presence of sediment, which includes the risk of blocking the outlets, particularly in the event of local earthquakes, and erosive action of sediment laden water on the outlet works and the turbine machinery. If specific measures are not taken to manage the reservoir on a sustainable basis, sedimentation can result in increasing maintenance costs and, eventually, to the scheme becoming inoperative.

The numerical models used to simulate sediment movement in reservoirs are relatively complex and rely on extensive field data. In particular, long records of river flows upstream of the reservoir are required and these, typically, should cover 30 or 40 years. Such records enable typical annual sequences to be developed and these are fed into the models at the upstream boundary. These sequences may or may not be factored, depending upon estimates of the effects of climate change.

In addition to the river flow data, numerical models need data for the input of sediments at the upstream boundary. The input of fine sediments is based upon estimates of sediment yield from the catchment and the input of the coarser sand and gravel sizes are usually based upon field measurements taken in the river upstream of the reservoir. The models compute the deposition and erosion of the various sizes of sediment separately and hence show how the sediments within the reservoir will vary in space and time. Typically, the coarsest sediments will be deposited at the upper end of the reservoir and the finer sediments will migrate further towards the dam.

Additionally the models require a knowledge of how the reservoir is operated. Water levels in the reservoir vary throughout the year, depending on the natural inflows and the outflows which are managed to satisfy the need for water supply and the development of hydropower. The instantaneous water level within the reservoir is one of the factors which affect sediment deposition or erosion.

Verification of model performance

If a reservoir has existed for a number of years it is useful to check the model performance by simulating the period between dam construction and the time of the study. Changes in reservoir bed levels and reservoir volumes can then be checked against field observations. The results can also be refined by minor adjustments to the input parameters and/or technical factors within the model itself.

Figures 13 and 14 show verification data from a study of Tarbela reservoir on the Indus River, Pakistan. The dam was built in 1974 and field observations were available up to 1996. These figures give an illustration of the accuracy which can be obtained given good field data.

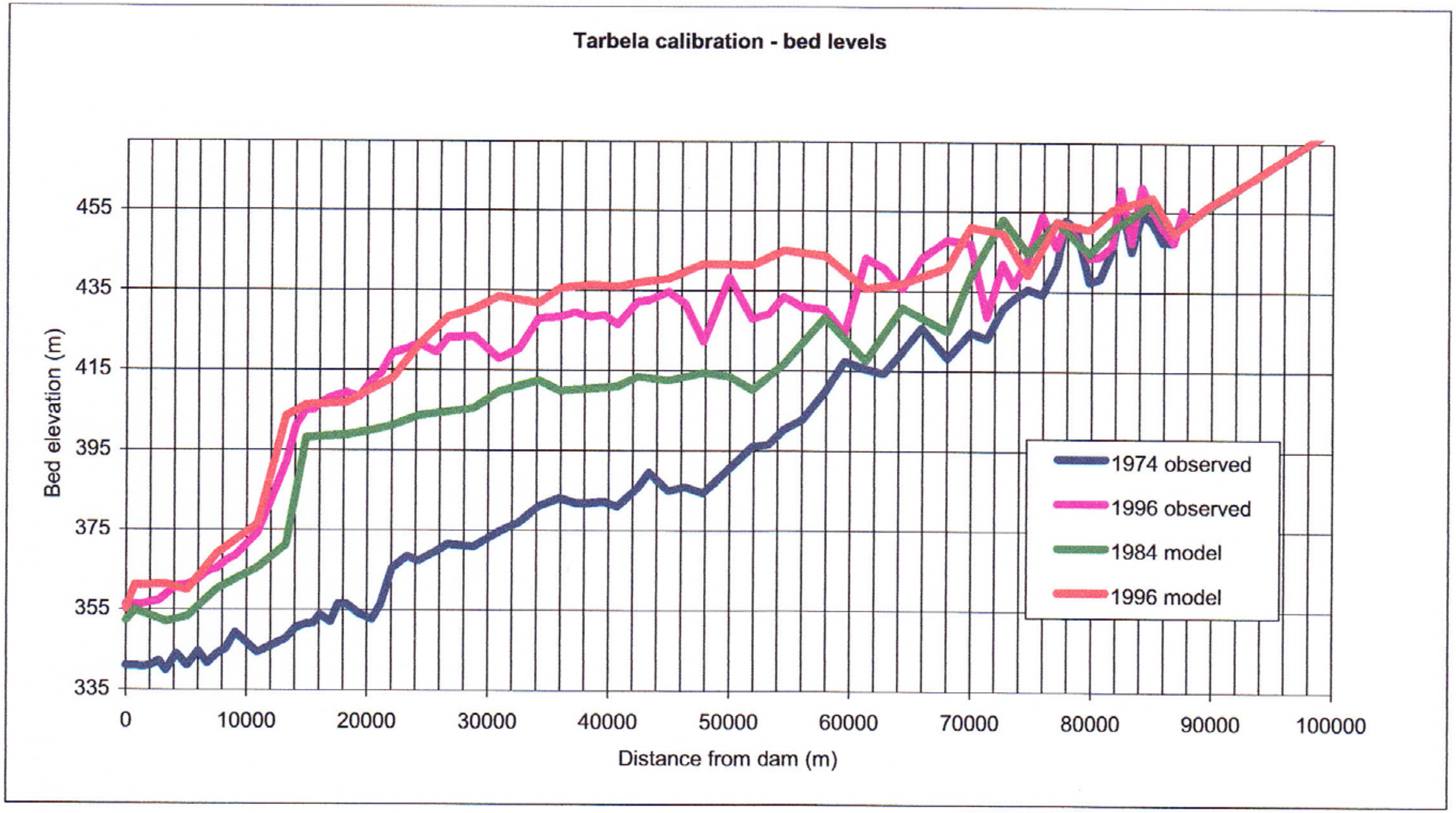

Figure 13 **Model verification for reservoir bed levels, Tarbela, Pakistan**
Source: **W R White (2001)**

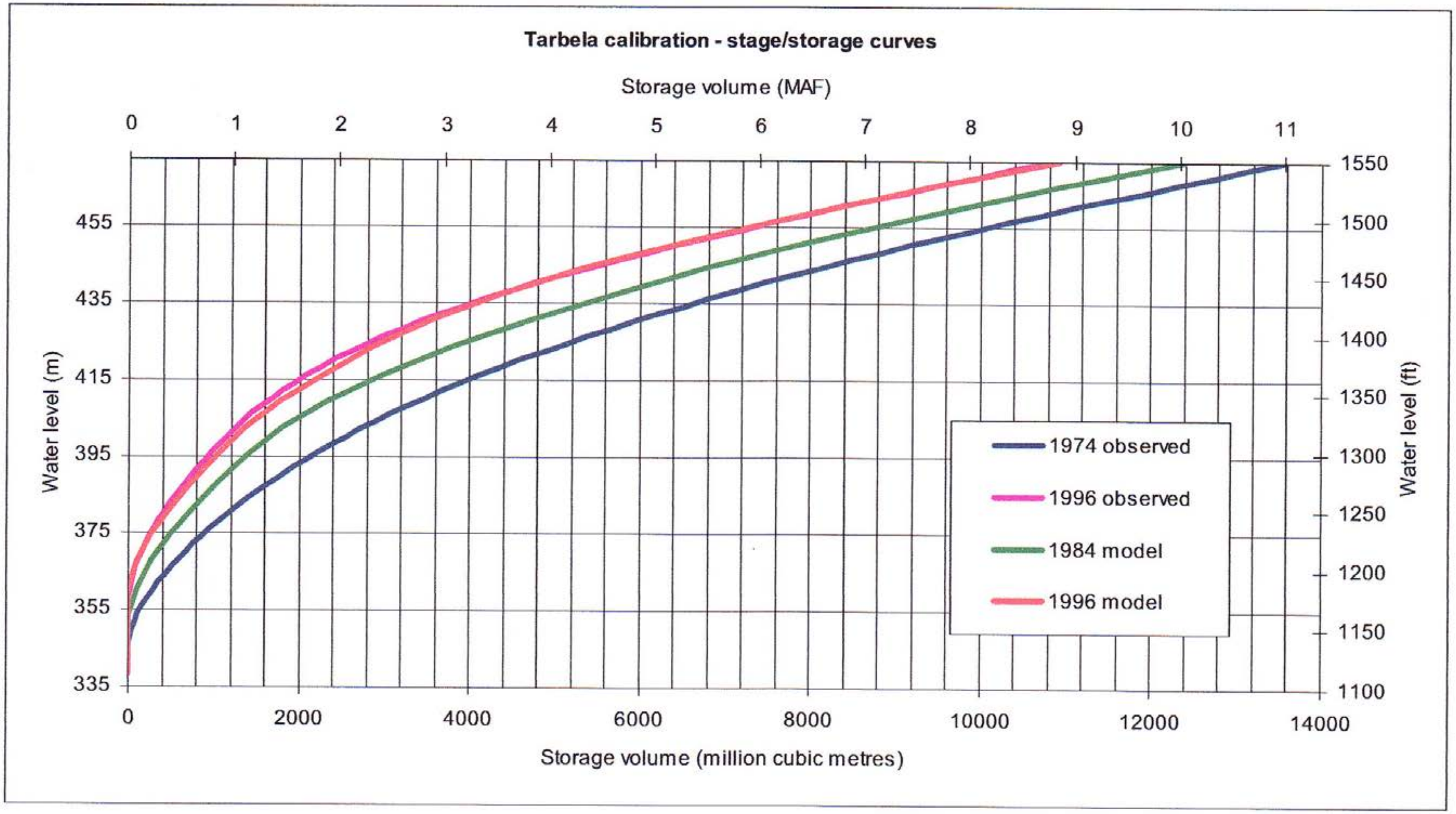

Figure 14 Model verification for reservoir volumes, Tarbela, Pakistan
Source: W R White (2001)

Future predictions as affected by reservoir operational policies

Generally speaking, water and sediment inflows to reservoirs remain similar throughout the life of the reservoir. They can be affected by man-made changes in the catchment area and also by climate change but these changes are usually small over the anticipated life of the reservoir. However, various strategies can be adopted to extend the life of reservoirs. These include changes to the operating sequences in terms of reservoir levels and, in extremis, the removal of sediments from the reservoir by mechanical excavation or hydraulic flushing.

Several scenarios are often developed for the operation of the reservoir and appropriate numerical model runs are used to explore the advantages and disadvantages of each scenario.

Figure 15 shows an example of the prediction of future sedimentation at Tarbela Dam, Pakistan, assuming that the operating rules are changed and that there is some flushing of fine sediments through the low level outlets at the dam.

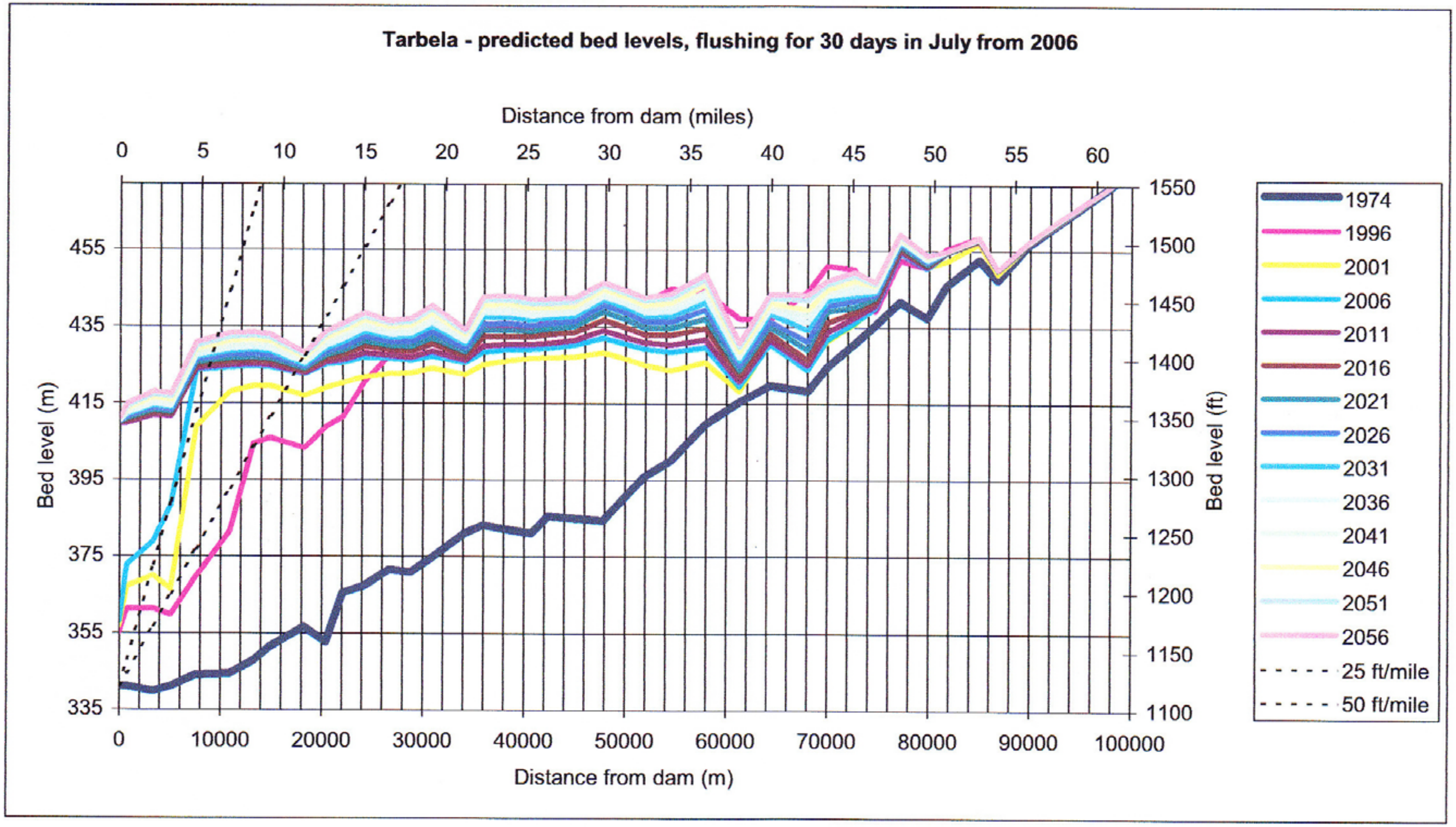

Figure 15 Future predictions for reservoir bed levels, Tarbela, Pakistan
Source: W R White (2001)

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Appendix

British and International Standards relating to sediments

Hydrometry - Functional requirements and characteristics of suspended sediment samplers	ISO/TS 3716:2006
Measurement of liquid flow in open channels - Methods for measurement of characteristics of suspended sediment	ISO 4363:2002
Measurement of liquid flow in open channels - Bed material sampling	ISO 4364:1997 Cor. 2000
Liquid flow in open channels - Sediment in streams and canals - Determination of concentration, particle size distribution and relative density	ISO 4365:2005
Hydrometry -- Methods for assessment of reservoir sedimentation	ISO 6421:2012
Liquid flow measurement in open channels -- Sampling and analysis of gravel-bed material	ISO 9195:1992
Hydrometry -- Measurement of liquid flow in open channels -- Methods of measurement of bedload discharge	ISO/TR 9212:2006