Sediment control in wadi irrigation systems

P. Lawrence
Hydraulics Research, Wallingford, UK

1. Introduction

Hydraulics research has monitored the design and performance of irrigation offtakes for three wadi systems (Rima, Zabid and Mawr) in the Yemen Arab Republic. This paper is drawn from the experience gained during these projects, and from research into improved design methods for sediment control structures.

The wadis that cross the Yemen coastal plain (Tihama) have steep, (0.5 to 1 percent) bed slopes, and flow in a series of multipeaked flash floods. Discharges can rise to more than 1 000 m^3/s, returning to less than 1 m^3/s in 4 to 10 hours, and stream velocities can exceed 4 m^3/s (Lawrence 1982).

In floods the wadi bed scours to depths of 1 m or more, and very high concentrations of bed material are transported. Data collected with automatic sediment sampling equipment in Wadi Zabid shows that such concentrations will exceed 10 percent by weight in large floods, although the sediment is mostly fine sand (Lawrence 1986a).

Sediment concentrations in floods exceed the capacity of conventional irrigation canals by at least an order of magnitude. Without effective sediment control canals silt up reducing discharge and conveyance capacities. In one silted wadi irrigation canal maximum discharge was only 40 percent of the canal design discharge, and this flow was maintained for only a few minutes (Lawrence, 1986b). Sediment concentrations must be reduced to match canal transporting capacities to reduce the annual costs of canal desilting.

Sediment deposition upstream from weirs increases bed levels, filling in the pool produced by a raised weir crest. This can lead to difficulties in diverting low flows, particularly if there are offtakes on both banks.

The design of an offtake or sediment control structure for a wadi irrigation system is problematic. There are very large variations in the flows and sediment loads arriving at the point of diversion, and for most of the time all of the wadi flow will have to be diverted to the canal. To compare the various sediment control options, quantitative performance prediction methods must be used. However, reliable tested methods are only available for a few sediment control structures; in some cases the only information will be some total load samples collected in bottles at low flows.

In the absence of measured data, particularly at flood discharges, bed material sediment loads were estimated using sediment transport equations. However, these can have a very wide error margin when used to predict wadi sediment transport rates (Lawrence, 1986b).

The first sections of this paper are thus concerned with the methods that are available to measure or predict wadi sediment loads and this is followed by some examples of the effects of sediment in the Wadi Zabid irrigation system. The sediment control options that are open to the designer are then discussed in the context of a rational, quantitative design procedure. The options that are available include:

(a) Excluding, or at least reducing, the concentrations of bed material sediments that are allowed to enter the canal head reach at the headworks.

(b) Removing excess sediment with a sediment extractor, usually located in the canal head reach.

(c) Designing the canal to transport the high sediment concentrations that will be admitted.

(d) Accept that a conventionally designed canal will silt up, and make the appropriate arrangements for routine desilting.

The recurrent costs of desilting will not usually make the last option (d) very attractive for an operating authority, while option (c) will result in a cheap (no drop structure), unconventional design, and high bed material sediment concentrations entering the fields. However it should not be rejected out of hand, traditional canal systems appear to have functioned effectively, in some cases over many centuries.

The final section of the paper presents the case for further sediment monitoring at existing wadi offtakes and main canal systems to provide the data that is required for improving both the design procedures and the performance of wadi sediment control structures.

2. Sediment transport in wadis

2.1 Definition of terms

There is still a great deal of confusion concerning the terms used to describe sediment transport mechanisms and the size range of the transported sediments. In this paper the definitions adopted are those presented in the FAO Irrigation and Drainage Paper 37 (FAO, 1981).

Wash load concentrations are seldom very well correlated with channel parameters such as discharge, and cannot be estimated using sediment transport functions. The capacity of a stream to transport washload is almost unlimited; washload concentrations are supply controlled.

Secondly, defining wash load in terms of size can only be true for one set of hydraulic conditions. Silt carried as washload in a river can be transported as bed load in a reservoir. There is no general agreement as to when wash load becomes suspended bed material load or vice versa, although definitions for wash load based on suspension criteria have been proposed, De Vries (1981). In this paper we adopt the usual convention that material smaller than 63 microns should be treated as wash load. A justification for this assumption for flows in Wadi Zabid is presented in Lawrence (1986).

Thirdly, a similar problem of definition occurs between suspended bed material load and bed load, particularly when attempting to define what is being measured with field sediment sampling equipment as discussed by Bolton (1985). In wadis, the bed material usually contains a wide range of sediment sizes, and the transport rates are dominated by the finer materials which are transported as suspended bed material. In wadis, however, bed load is unlikely to represent more than about 10 percent of the bed material load (FAO, 1981).

The first two points may seem a little academic to an engineer concerned with the design of a spate wadi irrigation system. The last is not. Wash load is usually transported through irrigation canal systems and deposited onto the fields. Therefore concentrations of bed material are of interest in the design of canal systems or sediment control structures. Unfortunately many hydrological studies in which sediment is measured do not distinguish between wash load and suspended bed material load. Bottle sampling techniques providing estimates of total suspended load are employed. providing little useful data for the design of sediment control structures.

3. Field measurements

3.1 Introduction

Effective sediment control is necessary for the viability of wadi irrigation systems, but there has been little collection of sediment transport data. Much of the data that has been collected in conventional hydrological studies is for total load. In this section the requirements for data and the application of conventional bottle sampling methods are briefly discussed, followed by a more detailed description of automatic pump sampling techniques.

3.2 Data requirements

The data needed to check sediment transporting capacity and to design sediment control structures will depend on the severity of the sediment problem, and the methods chosen for its alleviation. The following list is a minimum requirement:

(a) Concentration and size range of bed material sediments as a function of wadi discharge. (Discharge should always be measured at the same time that sediment concentrations are measured).
(b) Bed material size grading curves, where flows and sediment loads are measured, and at the site or sites of the offtake structures. Collect samples from at least five trial pits at each location. As the size of the material forming the channel will probably be very varied, bed engineering judgement is needed to assemble a "representative" bed material size grading curve.
(c) Bed material specific gravity.
(d) Wadi bed cross sections and stage discharge curves at the measurement and offtake locations.
(e) Water surface slope at known discharges at the measurement locations.
(f) Channel bed slope at the measurement and offtake locations.
(g) Water temperature.

This list is not exhaustive. Flow statistics for different return periods will be required to compute seasonal

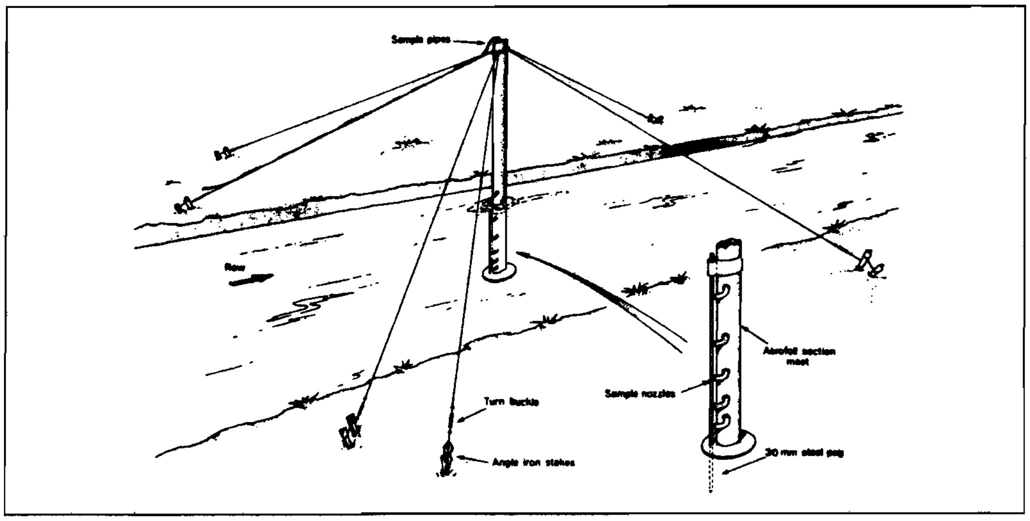


Figure 1 Sketch of typical pump sampling installation

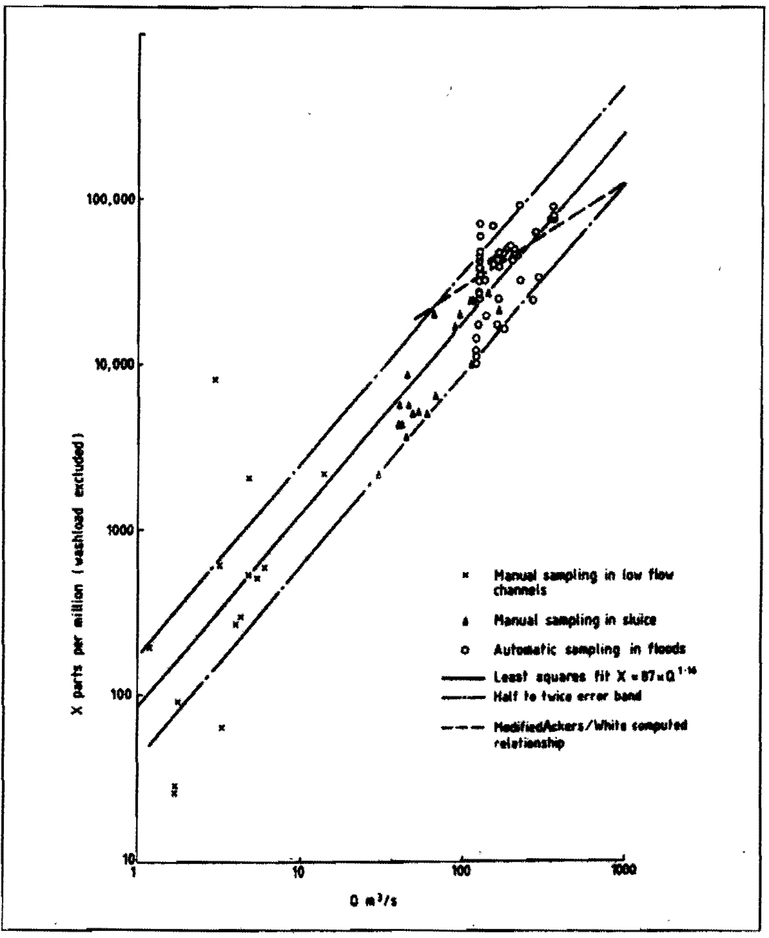


Figure 2 Wadi Zabid—sediment concentration as a function of discharge

sediment balances. Here we are concerned only with item (a), the measurement of bed material sediment concentrations.

3.3 Sediment measurement with bottle samplers

Despite a large number of methods for measuring sediment transport rates, most hydrological studies use one or another of the "standard" bottle sampling techniques. Methods and procedure, to evaluate and standardise these techniques, are described in ASCE (1975). An excellent description of bottle sampling methods in wadi conditions is presented in FAO (1981). However, it is worth highlighting the reasons for proposing, as we do later in this paer, that an alternative sediment sampling method is used in wadis.

Floods in wadis usually last only a few hours, and most primary gauging sites are located several hours drive from the headquarters of the monitoring organization. Thus, to collect data in floods, when most of the transport of bed material sediment occurs, a team of observers has to be permanently stationed at the gauging site.

Bottles are lowered from a cableway into the flow, and, if depth integrating samplers are used, moved to the channel bed and back at constant rates. As velocities can exceed 4 m a second, very heavy counter weights, which are difficult to handle, have to be used. At high flows it is usually impossible to get the bottle to the near bed zone with weights of a practical size. In addition large quantities of trash, transported by the leading edge of a flood wave, are trapped on the suspension gear.

It is thus understandable that little sediment data has been collected with bottle samplers during the important high flow periods. In the data set, presented in FAO (1981), for Wadi Najran only three data points were measured for a discharge larger than 200 m³/s, while the stage discharge relationship has data points up to 1000 m³/s.

The highest flow at which a bottle sample had been collected in a study carried out in Wadi Zabid prior to the construction of the diversion structures was 50 m³/s. Flood discharges in excess of 1700 m³/s have been recorded in this wadi.

Summarizing, conventional bottle sampling techniques are difficult to use in high flows. This means that little data have been collected during the highest flow periods.

A further objection to bottle sampling techniques is, Bolton (1983), that the samples are too small to be analysed to yield size grading curves of the suspended material. However, in wadi measurment applications, at least at high flows, the sediment concentrations are orders of magnitude larger than those observed in perennial rivers with milder slopes, and a reasonable quantity of sediment can be collected in a sample bottle.

3.4 Pump sampling

Because of the limitations of bottle sampling Hydraulics Research has used Pump Sampling techniques for many years. A sketch of a typical pump sampling installation is shown in Figure 1. This shows a number of nozzles fixed to

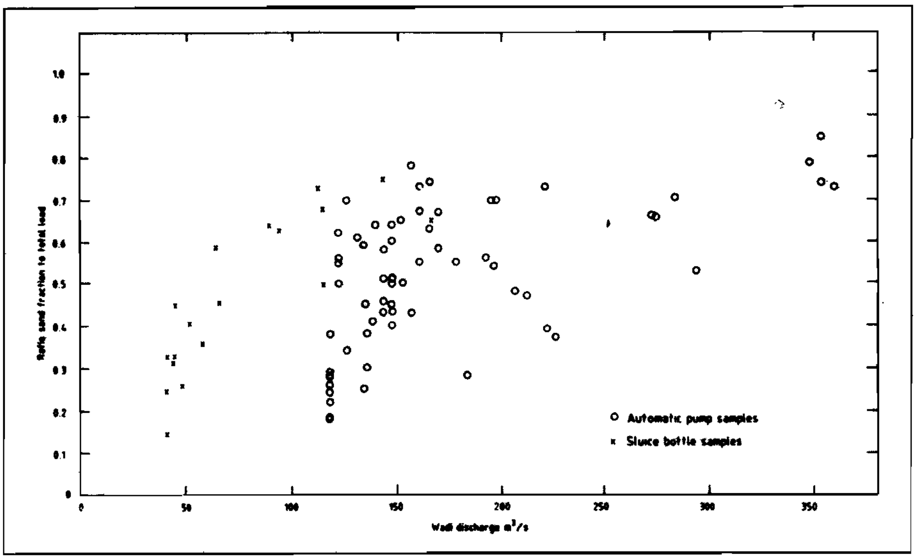


Figure 3 Ratio of sand fraction to total load sediment concentrations

a rigid mast mounted in the river bed. Alternatively nozzles can be suspended from a cableway. Where stream velocities are very large, as in wadis, nozzles can be bolted to rock outcrops or onto small purpose built concrete structures.

Water is pumped from each nozzle, in turn, through a 63 micron filter to remove washload which can be sampled at the filter outlet if required. Normally at least 10 litres of water should be pumped, depending on the application. Sampling at each nozzle lasts several minutes, providing some temporal averaging. More importantly, at least in perennial rivers where sediment concentrations are usually low, enough bed material sediment can be collected to enable individual samples to be size graded.

Sediment flux is calculated first by fitting the point concentrations to a theoretical concentration profile, and then integrating the product of the concentration and velocity profile through the depth.

The pump sampling methods used by Hydraulics Research have been described by Crickmore and Abed (1975), and Bolton (1983 and 1985). Atkinson (1987b) described methods for assessing the accuracy of pump sampling.

Studies carried out by the overseas unit at Hydraulics Research where pump sampling has been successful, are reported by Lawrence (1986a and 1986b), Fish et al (1986) and Fish (1987), Atkinson (1986b), Bolton (1985) and Amphlett (1984 and 1986).

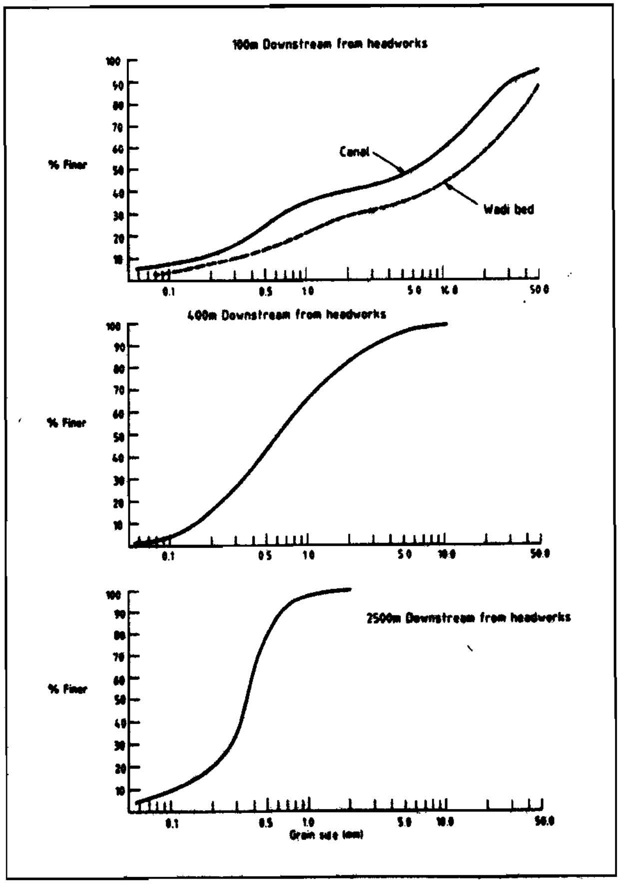
Automatic pump samplers were developed for rivers prone to flash floods. This equipment can be solar powered and deployed at remote sites. Sampling sequences are pre-programmed, and activated by rising water levels. Samples are stored in bottles which are retrieved after a flood for filtering, weighing, and size grading. Bed material and wash load sediment concentrations were measured using such equipment in Wadi Zabid in 1982 and 1983 (Lawrence, 1986b).

3.5 Sediment concentrations measured in Wadi Zabid

Figure 2 shows bed material sediment concentrations measured in Wadi Zabid during the Hydraulics Research study. Very high concentrations, approaching 100 000 ppm, were recorded in flood flows, but these are not out of line with concentrations measured in similar rivers elsewhere (FAO, 1981).

The material that was collected by the bottle sampler was very fine when compared with the size grading curve of the parent bed material. The finer particle sizes dominate in the suspended bed material load carried by wadi flows. The ratio of suspended bed material load to total load is shown in Figure 3. There is a lot of scatter, due in part to the poor correlation of wash load concentrations with discharge. However there is a tendency for the proportion of sand to increase at higher discharges. A similar result has been reported for rivers in the south-west of the USA which transport very high suspended sediment concentrations (Beverage and Cuthbertson, 1964).

Figure 4 Canal bed levels, Wadi Zabid



3.6 Measurement programme

Using automatic pump samplers it should be possible to collect the data at high flows required to construct a reasonably reliable bed material sediment rating curve. The cost of the equipment required for a two-year feasibility study, a few thousand dollars, is very small when compared with the costs associated with the results of inadequate sediment control.

3.7 Sediment transport functions

If measured data are not available, or sediment concentrations measured at low flows have to extrapolated, then sediment transport functions have to be used.

The performance of sediment transport functions has been reviewed by ASCE, (1975) and by White (1973). The former study showed that the mean ratio of observed to predicted transport rate was between 0.5 and 2 for only 64 percent of the comparisons for the best method that was tested.

All sediment transport functions contain empirical constants. The data use to develop and test them are derived mostly from perennial rivers, canals and laboratory channels. Prediction of wadi sediment transport rates are far more uncertain than indicated by White (1973), because of wide bed material sediment size gradings, unpredictable flows and high Froude Numbers. Therefore it is clearly preferable to measure bed material sediment transport rates during the feasibility study phase of large irrigation projects.

There are a large number of methods for predicting the sediment transporting capacity of an alluvial channel. Some of the more recent have the advantage of being developed or tested using a wide range of field and laboratory data. All these methods perform relatively well when tested against the data that is available. However, their one drawback is that they are not formulated to deal with wide bed material size grading often found in wadis, although some methods do take the grading into account. The methods listed above, when used with the single bed material sediment size suggested by their authors, usually D50 or D35, predict very low concentrations for rivers with a large range of bed material sediment sizes.

3.10 Predicting the size range of suspended bed material

An irrigation offtake is usually designed to exclude the coarser sediment fractions which are transported as bed load. The concentration and size range of suspended particles is likely to be of most interest in the design of a canal system or sediment control works. A method for predicting the size grading of the suspended bed material has been presented by Lawrence (1986(a) and (b)), and later modified in Atkinson (1987a) and can be used when suspended bed material size gradings are required for the design of sediment control structures.

4. Effects of sediment

In this section the effects of sediment on the performance

Figure 5 Bunay-Barry canal bed material size gradings

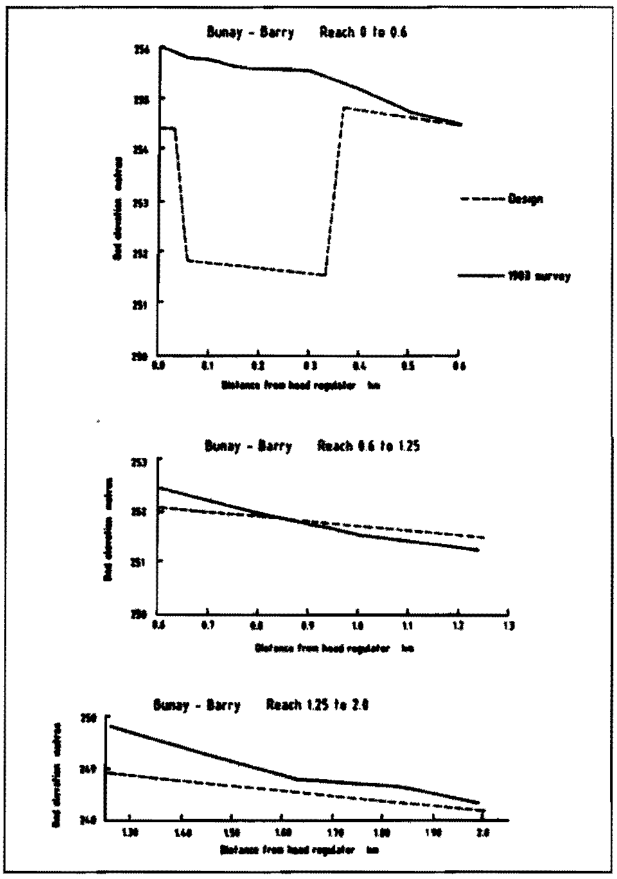
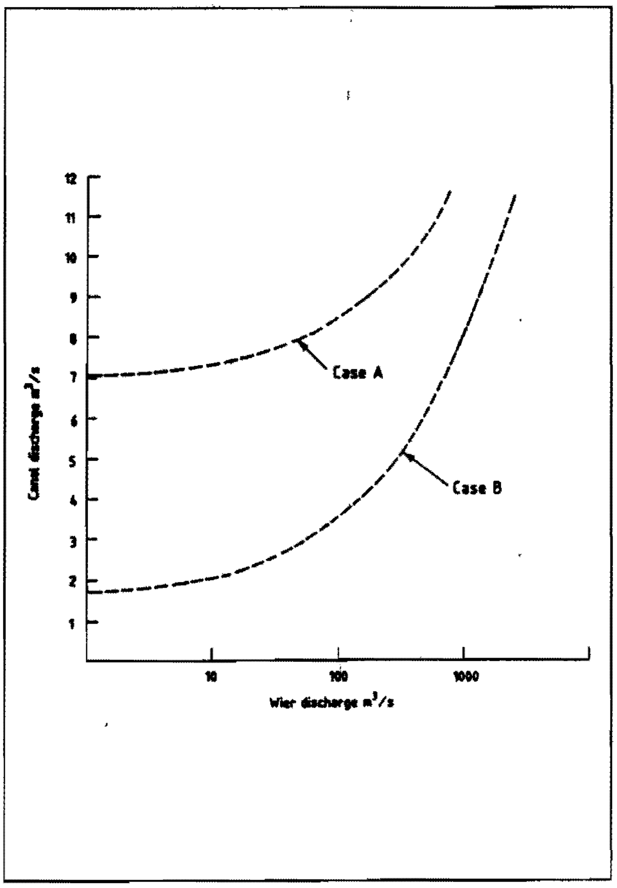


Figure 6 Bunay Barry canal discharge as a function of weir discharge



of a wadi irrigation system are discussed, using some data from Lawrence (1986b).

4.1 Deposition upstream from weirs

Weir construction raises water levels, increases flow depths and reduces flow velocities. This reduces sediment transporting capacity upstream from the weir causing bed material sediments from further upstream to settle close to the weir. Bed levels will start to rise and, in wadis can reach the weir crest elevation after one or two flood seasons, unlike flatter, perennial rivers where it can take many years.

There will also be a width adjustment at the weir if its crest length is larger than the "equilibrium" or regime channel width at the diversion site. The channel just upstream from the weir will return to its pre-construction width, depositing sediment in a shoal that will make diversion of low flows difficult if the structure is designed to have offtakes on both banks. However, in wadis a weir can usually be designed with a crest length less than the full channel width to pass the design flood. In this case the structure is usually completed by a bund connecting the weir abutment to the bank. Sediment deposition will occur in the dead water region in front of the bund, again making it difficult to divert water to an offtake located at the end of the bund. In fact it is usually impossible to divert water to offtakes located on both banks without mechanical intervention to keep approach channels open.

4.2 Sedimentation in canal systems

Wadi bed slopes are often 0.5 percent or larger. This is very much steeper than the canals in irrigation systems which therefore have a much smaller sediment transporting capacity. Unless the concentration of bed material sediments are reduced at or close to the intake, sediment will settle in the canal.

Figure 4 shows the rise in bed levels in the first three reaches of the Bunay-Barry canal in Wadi Zabid. (There is a drop structure at the end of each reach, which controls the water levels, and thus bed levels, at the downstream end of each reach.) Deposition of bed material sediments has increased the canal bed slope, as the system adjusted to increase its transporting capacity to match the sediment input and at the upstream end of the canal, were above the design water level by the time of the last survey (sediment was later removed during canal maintenance).

Figure 5 shows the variation in the size of the deposited sediment forming the bed of the same canal. Bed material in the head reach is almost as coarse as the parent wadi bed material. Without maintenance desilting coarse sediment would be transported further down the canal system, and eventually to the fields.

Sediment deposition resulted in a large reduction in the quantities of diverted water. The effect, due to the rise in the canal bed level just downstream from the intake gates, is illustrated in Figure 6.

In Figure 6 the quantity of water entering the canal is shown as a function of the discharge flowing over the weir. Two cases are shown: (a) for design bed levels, and (b) for the canal bed level at its higher 1982 elevation; in both cases the canal gate opening was 40 cm to prevent flood damage.

Curve (a) indicates that the weir does not begin to spill until the canal discharge rises to about 8 m^3/s, a little less than the maximum design discharge of 11 m^3/s. The canal discharge remains well controlled as the wadi discharge increases. Whereas in case (b) the weir starts to spill water at a canal discharge of only 1.7 m^3/s. The canal discharge does not reach its design value until the weir is passing a flow equivalent to the 1 in 50 year design flood.

Sedimentation in the canal head reach and a fixed canal gate opening, dramatically reduced the quantity of water diverted in flood flows to only about 30 percent of the flow that could have been passed (Lawrence, 1986b). (More water could have been diverted to the canal if the canal gate openings had been adjusted through flood recessions.)

The second effect of sediment deposition is to reduce the cross sectional area below the design freeboard. However, the greatest deposition occurs upstream from the canal reaches, which will usually be in a cut, and where water levels higher than design freeboards may be allowable. As the canal slope is larger than design when the canal is silted, the flow velocities are also larger, therefore the reduction in cross sectional area does not result in a loss in proportional discharge capacity.

This does not mean that canal sedimentation and the resultant increase in slopes is acceptable. Increasing the sediment transporting capacity of the canals implies higher concentrations of bed material sediments being transported to the fields, and eventually, problems of command at the field outlets.

5. Sediment control structures for wadi irrigation systems

5.1 Existing practice

Many of the new wadi irrigation systems replace "traditional" offtakes and canal networks. These (see LRDC, 1977, for a description of traditional systems in Wadi Rima) have evolved, in some cases over many centuries, in response to the constraints imposed by the flashy nature of the flows, the high sediment loads, and the local water distribution systems.

Traditional offtakes consist of low stone and brushwood deflectors built out into the wadi bed to intercept the low flow channels. The deflectors divert water to ungated canals which, at least in the head reaches, have bed slopes only a little less than the parent wadi. This system copes with sediment quite well. High sediment concentrations will enter the canal at medium flows, but at high flows the deflector washes out. The steep slopes produce high velocities preventing sediment deposition, although there will be some scour.

The sediment control measures that have been adopted in the "new" wadi irrigation systems include headworks with curved approach channels and vertical flow separation to exclude bedload. Sluiced settling basins, vortex tube and tunnel sediment extractors have been designed, although not always constructed, to reduce the sediment loads passed to main distribution systems.

The curved approach channel arrangements described by Smith et al (1980), has been used with some success in the PDR Yemen and Saudi Arabia. Most of the intakes in recently designed systems have a gated sluiceway with some vertical separation between canal and sluice flows, although it is not always clear whether they should be operated with continuous sluicing in floods or in the still pond mode.

Sediment control in the Tihama wadi irrigation systems has become increasingly sophisticated. In Wadi Zabid, the first to be "improved", sediment deposition can only be effectively controlled by dredging the canals during maintenance periods (Lawrence, 1986b). Tunnel undersluices at the offtake and an arrangement for flushing the canal head reach were included in the design of the Wadi Rima system. Twin sluiced settling basins and a relatively sophisticated gate operations policy, to reduce the entry of sediment, are to be used in Wadi Mawr.

5.2 Quantitative design procedures

Several different approaches to sediment control in Tihama wadi irrigation systems have been, and will continue to be, developed. However, this does not mean that the design of sediment control structures should not take place within a rational quantitative framework. A possible approach is outlined below.

(a) Estimate the concentration of bed material sediments transported by the wadi at the proposed location of the offtake.

(b) Decide on the maximum wadi discharge, and thus the maximum sediment concentration at which the canal will divert water.

(c) Determine the concentration enhancement or reduction factor that will occur at the point of diversion for the bed load and suspended bed material load.

(d) Estimate the bed material load sediment transporting capacity of the canal system.

5.3 Closure limit

Sediment can be prevented from entering the canal by closing the headworks gates, and excluding all water. Sediment concentrations will be reduced by limiting the wadi discharge at which the canal is operated; this can make a significant reduction in the cost of the sediment handling works.

A closure limit on the headworks will not necessarily reduce significantly the quantities of water diverted. The Tihama wadis of the Yemen Arab Republic often have a small dry season base flow, and although most of the available discharge flows in the flood season, a high proportion of the discharge occurs at relatively low flows, as in the case for Wadi Rima in the Yemen Arab Republic (DHV, 1979), tabulated below. Only 3 percent of the total annual discharge flows at discharges greater than 100 m^3/s. In the design that was eventually adopted for the Wadi Rima it was planned that 85 percent of the total annual discharge would be diverted (DHV, 1979). As very high discharges only occur for short periods of time, typically minutes rather than hours, closing the canal gates at a wadi discharge of, say, 100 m^3/s would result in a loss of canal supplies for only a few hours in an average year.

Table 1

Hydrograph range (m3/s)	Annual discharge in range (percent)
less than 2	53
2 - 5	21
5 - 10	11
10 - 20	7
20 - 50	4
50 - 100	2
100	3

5.4 Bed material load admitted to canal

Bed material sediment concentration in the water entering the canal is often larger than the concentration in the parent river. This is caused by secondary currents generated at the offtake. The extent of this phenomenon is very dependant on the configuration of the structure, its location relative to channel bends and other factors. At present there are no reliable tested methods of quantifying these effects at the design stage. A well designed physical model can give qualified quantitative results, and developments in mathematical modelling techniques should make it possible to make reasonable quantitative predictions in the near future (Atkinson 1987).

With frontal intakes the sediment concentrations of the suspended bed material load entering the canal will be approximately the same as those transported in the wadi. The same will be true if the offtake angle is not too large.

5.5 Canal sediment transporting capacity

The qualifications concerning the use of sediment transport equations discussed earlier in the context of predicting wadi sediment transport rates do not apply for canal flows. The methods listed earlier in the paper can be used to check on transporting capacity. However the usual tolerance on sediment transport predictions is something like 0.5 to 2.0 times the predicted concentrations. The bed slopes of existing systems can be used to indicate which of the equations yields the closest fit to observed conditions.

5.6 Sediment removal

It may not be necessary, if, indeed, possible, to match sediment input to transporting capacity at all times. However a sediment balance on a seasonal basis is necessary to avoid regular desilting.

Most of the sediment control methods described in the engineering literature were developed for run of river offtakes in channels with milder slopes, smaller sediment loads, and less extreme discharge variations than are found in wadis. While conventional structures can be used, the flow characteristics of wadis present some additional difficulties for the designer, some of these are listed below:

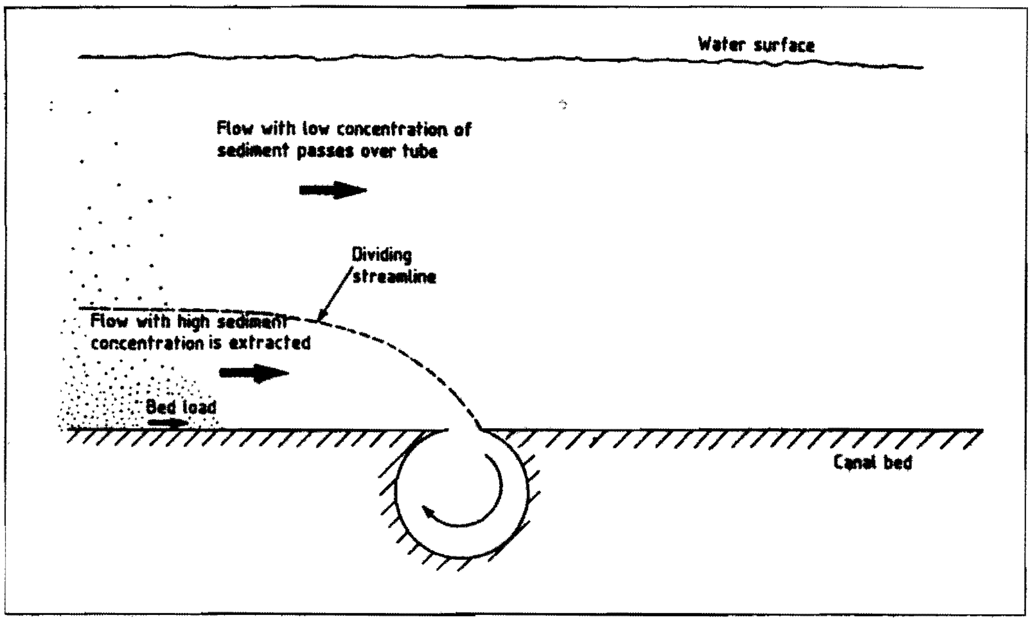


Figure 7
Elevation of a vortex tube sediment extractor with one tube

(a) When the wadi discharge is smaller than, or equals, the canal discharge, all the wadi discharge usually has to be diverted. Thus during the low to medium wadi flows, ie most of the time, additional water for hydraulic flushing can only be obtained at the expense of irrigation supplies.

(b) When all the flow is diverted, as is all the sediment transported by the wadi.

(c) The times when surplus water could be available for hydraulic flushing, ie in flood peaks, cannot be predicted in advance. Water for sediment flushing will be available only for short periods, in small floods lasting only minutes. Thus the operation of sediment control structures are difficult to plan, and very flexible operations rules will be necessary. In practise structures that use hydraulic flushing will have to use some of the water that could be diverted for irrigation.

(d) Sediment control structures are required to exclude or eject sediments with a wide range of sizes and for a wide range of concentrations.

Some of the structures which, despite these constraints, can be used to control sediments in wadi irrigation systems are described below. In some cases reliable methods of predicting the performance of the structures described are available and are briefly described. In all cases it is necessary to make some estimate of the likely performance if the quantitative design procedure outlined at the start of this chapter is to be followed.

5.6.1 *Canal sediment extractors.* Vortex tube and tunnel type sediment extractors have been widely used, particularly on the Indian sub-continent. Both function by diverting the bottom layers of flow from a canal to waste, and are therefore highly efficient at trapping coarse materials. Quantitative design and performance prediction methods for vortex tube and tunnel type sediment extractors have been developed by Hydraulics Research, Stanmuganathan (1976), Atkinson (1987a).

A vortex tube sediment extractor consists of one or more slotted tubes laid flush with the canal bed. One end of the tube is closed, the other is open and connected to an escape channel. Water and sediment flowing near the bed of the channel upstream are diverted through the vortex tube and discharged from the canal to an escape channel. A strong vortex flow is developed in the tube, which, provided the tube dimensions have been chosen correctly, prevents sediment from settling and blocking the tube. (Figure 7 shows a plan view of a vortex tube extractor.)

A tunnel type sediment extractor consists of a row of tunnels placed at the bed of a canal. Water and sediment flowing near the bed of the canal are diverted, usually to an escape channel. (This principle is shown in figure 8.) As the velocities in the tunnels are lower than those which occur in a vortex tube, the tunnels are prone to blockages, particularly when coarse sediments have to be diverted.

The sediment trapping efficiencies of vortex tube and tunnel type sediment extractors can be estimated using the method of Atkinson (1987a). A design manual with methods for determining the leading dimensions of the structures, structure location and the design of the escape channels is currently under preparation.

Both devices are relatively cheap to construct and can have high sediment trapping efficiencies for coarse material. However, their usefulness in wadi systems is reduced by the need to extract, and divert to waste, about 10 percent of the canal discharge. A method of overcoming this drawback was proposed for the Wadi Mawr in the Yemen Arab Republic. Vortex tubes, located just upstream from a drop structure, were designed to discharge into a settling tank. The water diverted through the extractor was returned to the canal, and the sediment deposits from the settling tank were returned to the wadi using jet pumps. It was estimated that only a small percentage of the canal discharge would

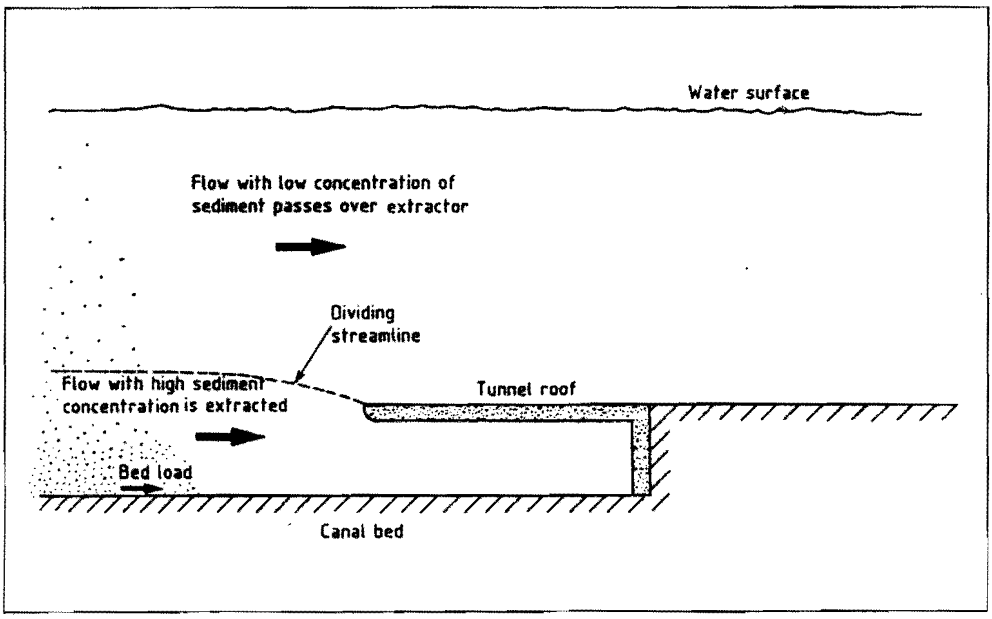


Figure 12 Elevation of a tunnel-type sediment extractor

be diverted, so the system was not constructed.

An extractor can be combined with other forms of sediment control. Intermittent use of the extractor would reduce sediment concentration during flood flows without reducing canal supplies.

5.6.2 *Settling basins.* Sluiced settling basins can be a very effective means of sediment control, although more expensive than a sediment extractor. The trap efficiency of a basin varies as it fills, therefore a prediction of the mean concentration of sediments leaving the basin is necessary. A section of canal is enlarged to reduce the velocity so that the sediment settles. When the basin is full the trapped sediment is flushed back to the river from a low level outlet.

There are a number of methods of designing settling basins, ranging in complexity from simple criteria based on settling velocity, to simulations using mathematical modelling. A fairly successful model that replicates observed behaviour of settling structures in Thailand, China and Indonesia has been described by Atkinson (1986), Fish (1987).

A relatively simple way to estimate initial basin size is to use the curves drawn by Camp (1946). Camp's curves do not account for turbulence at the inlet of the basin, which increases adaption lengths. Dhillon (1980) suggests that adaption lengths should be increased by about 20 percent to account for this (this publication contains a very useful practical review of methods of sediment control).

The maximum level to which sediment can be allowed to rise in the basin, and thus the point at which the basin should be sluiced, can be estimated from sediment transport equations. Sluicing performance is best predicted using the sort of model described by Atkinson (1986a).

Whatever design method is adopted, it should provide the designer with the following key predictions:

(a) The time taken for the basin to fill with sediment.
(b) The mean concentration and size range of the sediments leaving the basin during filling periods.
(c) The time and sluicing discharge required to flush the basin, and hence the volume of water required for sediment control.

Very large amounts of sediment that will be trapped in wadi irrigation systems, requiring frequent sluicing if the settling basin is not to be too big. Twin basins enable one basin to be sluiced while the other is filling, with no interruption to canal supplies provided that surplus water for flushing is available.

5.6.3 *Sediment exclusion at the headworks* Methods of sediment exclusion at offtakes are reviewed in Dhillon, (1980), and are also covered in ASCE (1975).

Offtakes are usually designed on the basis of past experience aided by model tests. At present there are no general, quantitative, and tested methods of predicting the sediment control performance of offtakes at the design stage.

6. Hydraulic models

The principle application of hydraulic models is to assist in the design of the offtake and river training works. "Mobile bed" models are usually used, at a scale of around 1 to 30, to 1 to 50. Important contributions to model design have been made by De Vries (1973), Novak and Cabelle (1981), and White (1982). A model facility constructed at Hydraulics Research to simulate wadi flows has been described by Sanmuganathan, Lawrence and Makin (1983) and Sanmuganathan and Lawrence (1984).

In this facility, flood waves are produced using an automatic controller that can be pre-programmed with any desired flood sequence. An automatic feeder adjusts the supply of sediment as the model discharge changes. The facility has also been used in a number of studies of the performance of irrigation offtakes for wadis.

It is impossible to simulate all the aspects of water and sediment movement at a reduced scale when water is the fluid in both the model and the prototype. A number of compromises have to be accepted when mobile bed models are used to model wadi flows since rapid flow variations and the wide range of sizes present in the bed present further difficulties. However, a carefully designed mobile bed physical model can produce valuable information for the designer. Nevertheless, some model predictions, for example the proportion of sediments that will be excluded with a particular intake geometry, will usually be heavily qualified, or only comparative.

The advent of computers with ever increasing processing power, and developments in mathematical simulations of the complex three-dimentional two-phase flows that occur at offtakes, will lead to the increasing use of mathematical models to predict sediment exclusion at irrigation offtakes.

However, monitoring the performance of existing structures could yield useful design information quickly, and at relatively low cost. This is discussed in the next section.

7. Performance monitoring

Unfortunately there is very little information describing the performance that has actually been achieved by sediment control structures under operational conditions. This can be contrasted with the large number of studies that are carried out before new structures and canal systems are constructed.

Monitoring of the performance of existing systems could have many benefits. One, providing designers with quantitative data to assist in the design of future systems, was touched on in the previous section. Others include improvement of the operation of existing structures, and the provision of data to develop and test quantitative performance prediction methods.

8. Conclusions

The following conclusions are drawn:

1. Sediment control in wadi irrigation systems is vital if the operating authorities are not to be burdened with high annual desilting costs.

2. The design of sediment control structures requires some basic data, such as the quantity of bed material sediments that are transported by a wadi at different discharges. It is suggested that this infomation is best obtained from automatic sediment sampling equipment deployed for one or two years during feasibility studies. It is very important to distinguish between washload and bed material load when field data is collected and analysed.

3. If no data are available, sediment transport functions have to be used to predict sediment loads. Sediment transport equations should be used that have performed reasonably well when tested against large data sets, with a modification to account for the wide bed material size gradings that are often a feature of ephemeral rivers. However, predictions made in this way will have a large uncertainty, and it is not wise to base the design of expensive structures on them.

4. A rational quantitative approach to the design of sediment control structures is advocated. However, design options can only be compared if the performance of sediment control structures can be predicted at the design stage. Reliable methods exist for some structures, but for offtakes it is still necessary to rely on model studies backed by engineering judgement.

5. Monitoring sediment loads at selected existing intakes and canal systems could provide data to improve future designs and to test new quantitative design procedures, as well as identifying ways of improving the effectiveness of the structures monitored. It is suggested that provisions for some performance monitoring are included in the funding arrangements for new wadi irrigation systems.

References

Ackers, P., & White, W. R., 1973. Sediment transport: a new approach and analysis. *Proc ASCE*, Vol 99 HY11.

Amplett, M. B., 1984. *A guide to some equipment and measurement techniques in soil erosion research*. Report OD 63, Hydraulics Research, Wallingford.

Amplett, M. B., 1986. *Reservoir sedimentation project, Dallao, Magat Catchment, Philippines*. Interim Report. Report OD 80, Hydraulics Research, Wallingford.

ASCE, 1975. American Society of Civil Engineers - *Manuals and Reports on Engineering Practice No 54, Sedimentation Engineering* (Vanoni, V. A., Editor).

Atkinson, E,, 1985. *The performance of weirs in rivers carrying high sediment loads: a field study in Northern Thailand: Interim Report*. Report OD/TN 15, Hydraulics Research, Wallingford.

Atkinson, E., 1986(a). *A model for the design of sluicing type sediment control structures*. Report OD/TN 18. Hydraulics Research, Wallingford.

Atkinson, E., 1986(b). *The performance of diversion weirs in rivers carrying high sediment loads*. Final Report on a field study in Northern Thailand. Report OD 86, Hydraulics Research, Wallingford.

Atkinson, E., 1987(a). *Field verification of a performance prediction method for canal sediment extractors*. Report OD 90, Hydraulics Research, Wallingford.

Atkinson, E., 1987(b). *Sediment flux measurements using pump samplers*. Paper for Indo British Workship on Sediment Control, Chandigarh, India, February 1988 (available from Hydraulics Research, Wallingford).

Bagnold, R. A., 1980. An empirical correlation of bedload transport rates in flumes and natural rivers. *Proc R Soc Lond* A372 pp 453-473.

Beverage, J. P., & Cublertson, J. K., 1964. Hyperconcentrations of suspended sediment. *ASCE* Vol 90 HY6, November 1964.

Brownlie, W. R.. 1981. *Prediction of flow depth and sediment discharge in open channels.* W M'Keck Laboratory of Hydraulics and Water Resources. California Institute of Technology Report KH-R-43.

Bolton, P., 1983. *Sediment discharge measurements and calculation.* Report OD/TN 2, Hydraulics Research, Wallingford.

Bolton, P., 1985. *Sediment discharge measurement: analysis and results from Sagana, Kenya.* Report OD 64, Hydraulics Research, Wallingford.

Camp, T. R., 1946. Sedimentation and the design of settling tanks. *Paper 2285 Trans ASCE* Vol III 1946.

Crickmore, M. J., and Aked, R. F., 1975. *Pumped samplers for measuring sand transport in tidal waters.* IERE Conf on Instrumentation in Oceanography, Bangor, North Wales.

DHV, 1979. *Wadi Rima irrigation development feasibility study Vol II.* DHV Consulting Engineers, Amersfoort, Netherlands.

Dhillon, G. S., 1980. *Sediment exclusion - a state of art report.* Study Report No 7, Central Board of Irrigation & Power, N Delhi, India.

Einstein, H. A., 1950. *The bed load function for sediment transportation in open channel flows.* Tech Bulletin No 1026, US. Dept of Agriculture soil Conservation Service, Washington DC.

Engelund, F., & Hansen, E., 1967. *A monograph on sediment transport in alluvial streams.* Taknish Vorlag, Copenhagen.

FAO, 1981. FAO irrigation and drainage Paper 37, *Arid Zone Hydrology*, FAO, Rome.

Fish, I. L., Lawrence, P. & Atkinson, E., 1986. *Sedimentation in the Chatra Canal, Nepal.* Report OD 85. Hydraulics Research, Wallingford.

Fish, I. L., 1987. *Field measurements at Karangtalun sluiced settling basin, Togyakarta, Indonesia.* Report OD/TN 31/ Hydraulics Research, Wallingford.

Lawrence, P., 1982. *Performance of gabion bed stabilisers in Wadi Rima, Yemen Arab Republic.* Report OD 49, Hydraulics Research, Wallingford.

Lawrence, P., 1983. *Wadi Rima - hydraulic model investigation.* Report OD 54, Hydraulics Research, Wallingford.

Lawrence, P., 1986(a). *Measurement of discharge and sediment flows in Kansal Choe, 1985.* Report OD 79, Hydraulics Research, Wallingford.

Lawrence, P., 1986(b). *Wadi Zabid diversion structures - field performance.* Report OD 73, Hydraulics Research, Wallingford.

LRDC, 1977. *Irrigation and agriculture development in Wadi Rima, Yemen Arab Republic Vol 1 and 2.* Land Resources Development Centre, Ministry of Overseas Development, UK.

Novak, P., & Cabella, J., 1981. *Models in hydraulic engineering.* Pitman UK.

Rijn, L. C. (Van), 1984. Sediment transport. *ASCE Jrnl of Hydr Eng*, vol 110 Nos 10, 11 & 12.

Sakhuja, V. S., 1987. *A compilation of methods for predicting friction and sediment transport in alluvial channels.* Report OD/TN 2, Hydraulics Research, Wallingford.

Sanmuganathan, K., 1976. *Design of vortex tube silt extractors.* Report OD 6, Hydraulics Research, Wallingford.

Sanmuganathan, K., Lawrence, P., & Makin, I. W., 1983. *A variable rate wet sand feeder for scale models of sediment laden flash floods.* IAHR, Moscow 1983.

Sanmuganathan, K., & Lawrence, P., 1984. *Hydraulic modelling of structures in rivers prone to flash floods.* IAHR, Asian Pacific Regional Division, IV Congress, Chiang Mai, Thailand.

Smith, K. V. H., Hewett, R. M. G., & Lawson, J. D., 1980. Headworks for spate irrigation systems. *Civil Engineering UK*, pp 32-41, September 1980.

Vries, M. (de), 1973. *Design and operation of movable-bed river models.* Delft Hydraulics Laboratory, Publ No 108.

Vries, M. (de), 1981. *On measurements of sediment transport in open channels.* Special Lecture, South East Asia Regional Symposium on Problems of Soil Erosion and Sedimentation, AIT, Bangkok.

White, W. R., Milli, M., & Crabe, A. D., 1973. *Sediment transport: an appraisal of available methods.* Report IT 119, Hydraulics Research, Wallingford.

White, W. R., 1982. *A novel loose boundary model for investigating sedimentation problems at an intake.* Int conf on Hydraulic Modelling of Civil Engineering Structures, Coventry, England.

Yang, C. T., 1979. Unit stream power equation for total load. *Jrnl of Hydrology* 40 pp 123-138.