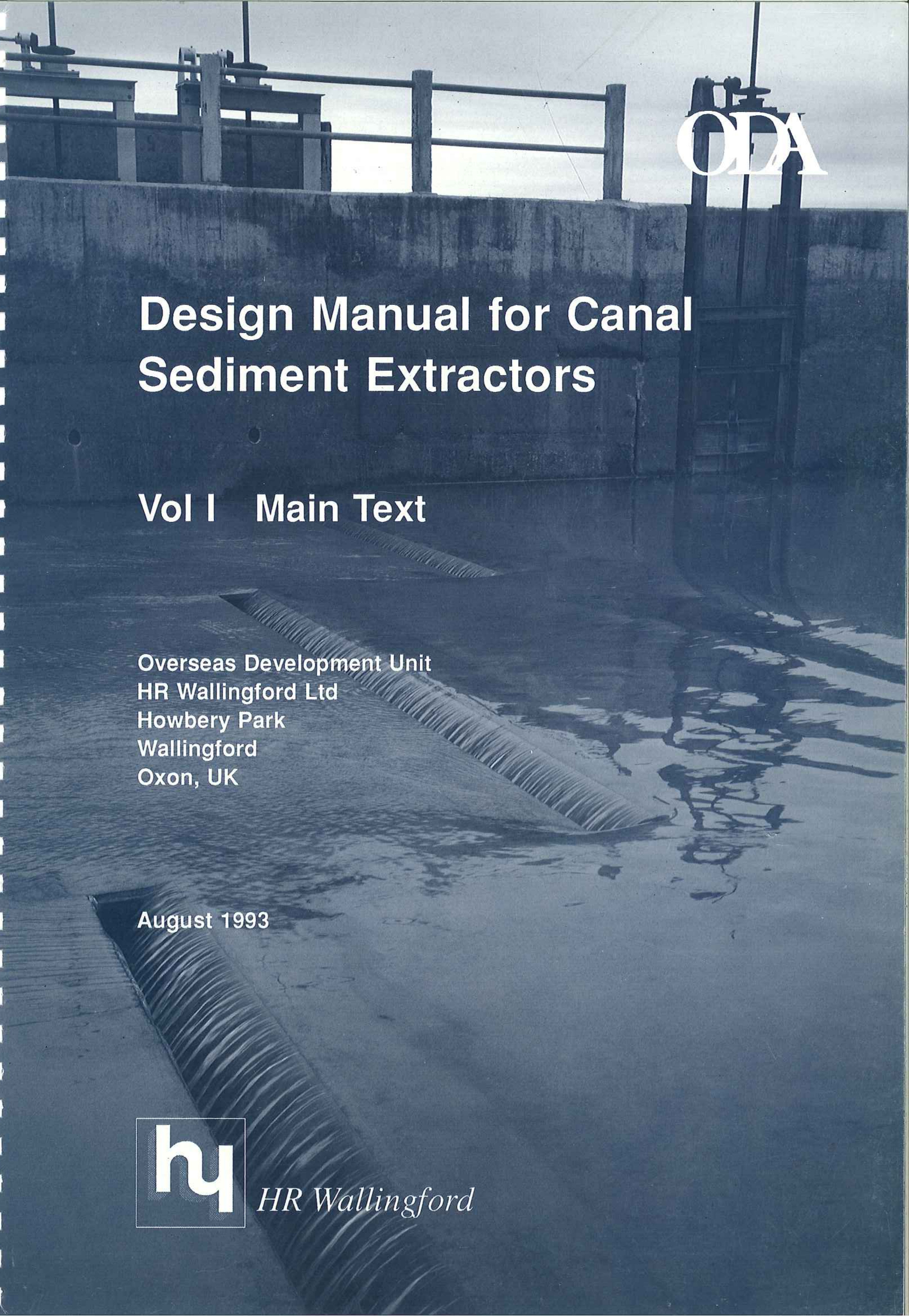

ODA

Design Manual for Canal Sediment Extractors

Vol I Main Text

Overseas Development Unit
HR Wallingford Ltd
Howbery Park
Wallingford
Oxon, UK

August 1993

HR Wallingford

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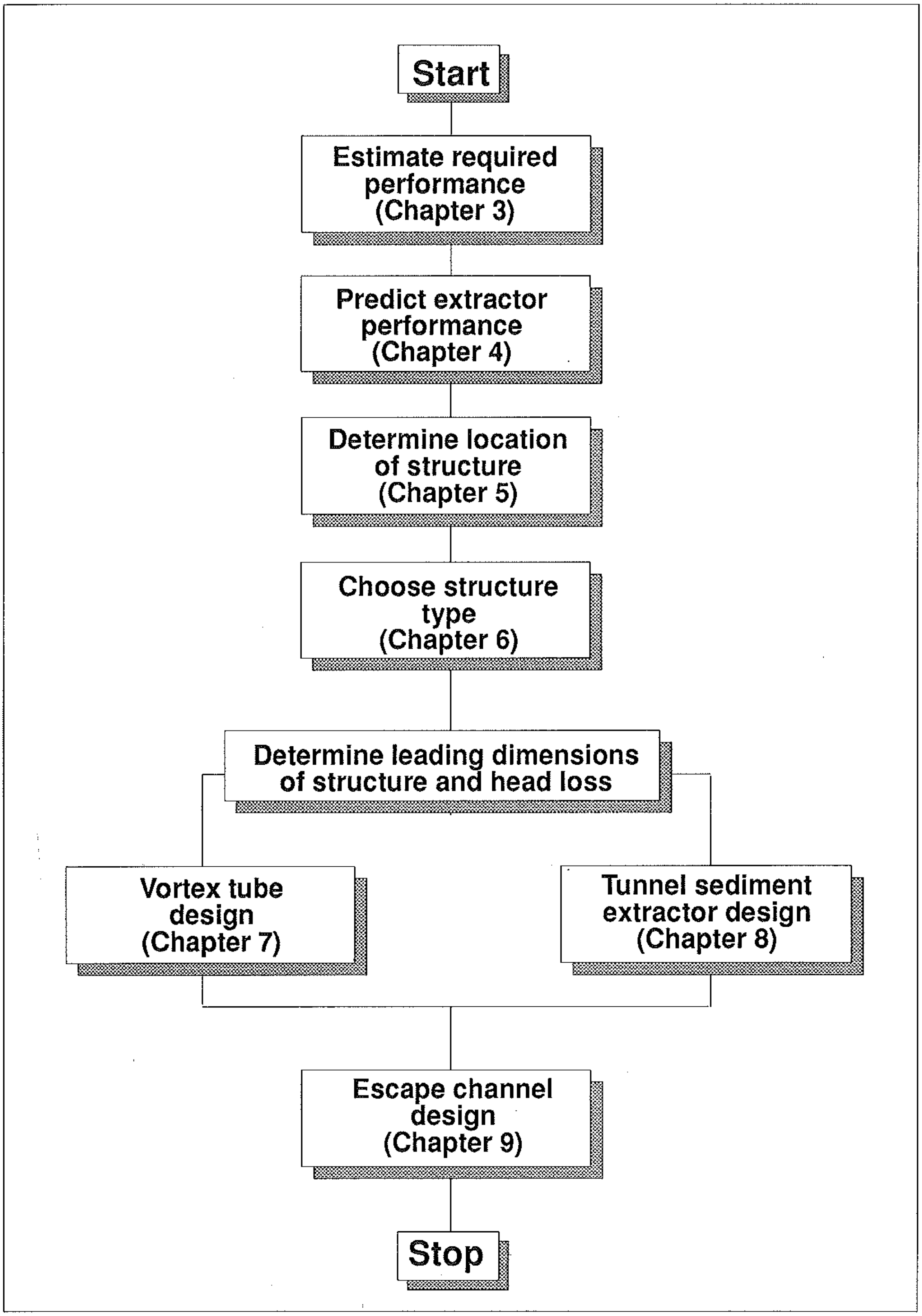
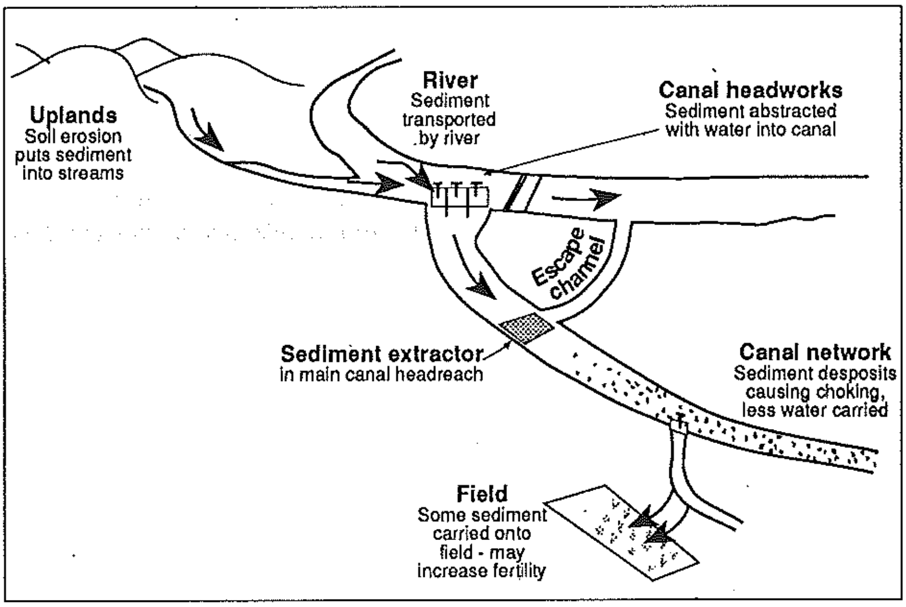


Flow chart indicating principal steps in using the manual

Preface

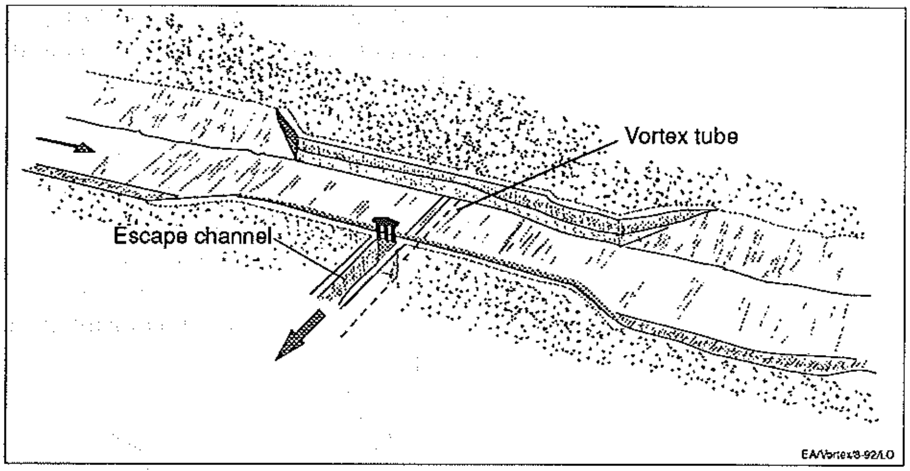
Water diverted from rivers to irrigation canals can contain high concentrations of bed material sediments. As the sediment transporting capacity of canals is usually smaller than that of rivers, sediment settles, reducing the quantity of water that canals can supply. Removing sediment deposits is expensive, and represents a major proportion of maintenance costs in many run of river irrigation systems.

Sediment concentrations entering a canal must be reduced to match the canal's transporting capacity if sedimentation is to be avoided. There are several means of achieving this, based on excluding sediment at the offtake, and/or extracting sediment from the canal head reach. The method chosen will depend on local factors such as the size and quantity of sediment that has to be removed, and the availability of both head and water for sediment flushing.



ODU at HR Wallingford has carried out research to provide engineers with reliable quantitative design methods for sediment control structures for a number of years. This manual is one of the results, and sets out methods for designing and predicting the performance of Vortex Tube and Tunnel sediment extractors. Using the methods an engineer can predict the sediment trapping efficiency that will be achieved, the quantity of water and the head needed to operate an extractor, determine its optimum location, principal dimensions, and the cross-section and slope of the escape channel that is used to return extracted sediment to a river. Calculations can be carried out using design tables or with DACSE microcomputer software which is also available from HR Wallingford.

Design methods, particularly the method used to predict sediment trapping efficiency, have been extensively field tested. This has only been possible with the willing collaboration of irrigation departments in many countries. The organisations who collaborated with HR Wallingford are acknowledged in Chapter 10.



A vortex tube sediment extractor

The manual and the research on which it is based, was supported by the British Government's Overseas Development Administration.

List of symbols

a	Reference level	
A	cross-section area of flow in a channel (also a coefficient in Ackers and White formulae in Appendix 2)	(m^2)
A_n	new cross-section area in iterative method for depth prediction	(m^2)
b	bed width of a channel	(m)
b_d	channel width at upstream end of escape channel	(m)
b_e	sum of widths of all tunnels at exit section	(m)
b_m	mean width of a channel	(m)
b_t	width of a tunnel in a sediment extractor	(m)
b_{te}	width of an individual tunnel at exit section	(m)
c	A coefficient in Ackers and White formulae	
c_F	A constant in Brownlie's transport equation	
C	Chezy's coefficient	
C'	Chezy's coefficient relating to grains	
C_a	Concentration at reference level a	
C_{It}	constant in method for depth prediction	
d	diameter of vortex tube	(m)
d_d	flow depth at upstream end of escape channel	(m)
D_{10}	sediment grain size at which 10% by weight of the material is finer	(mm)
D_{50}	sediment grain size at which 50% by weight of the material is finer	(mm)
D_{90}	sediment grain size at which 90% by weight of the material is finer	(mm)
D_{90max}	maximum allowable D_{90} size in the canal bed material	(mm)
D_{gr}	Dimensionless particle size	
D_N	sediment grain size at which N% by weight of the material is finer	

List of symbols continued

D_{max}	maximum size of sediment reaching the extractor	(mm)
D_{maxT}	maximum size of sediment which the canal flow can transport	(mm)
D_S	Particle size of suspended sediments	
F_{fg}	Sediment mobility related to total shear stress	
F_g	Grain Froude number	
F_{gr}	Mobility number	
F_{gCr}	Critical grain Froude number	
F_g^*	F_g value at transition	
Fr	Froude number in canal, defined in Section 4.3 (iii) and 5.3 (iii)	
g	gravitational constant, $g = 9.81 m/s^2$	
h	flow depth in a channel	(m)
h'	Defined $h(u'_*/u_*)^2$ (m)	
h_e	tunnel height at exit section	(m)
h_f	tunnel height which remains unblocked (See Figure 8.7)	(m)
h_g	guess for h in iterative method for depth prediction using Manning's equation	(m)
h_{og}	old guess for h in iterative method for depth prediction using Manning's equation	(m)
H	head loss in tunnel due to friction	(mm per m)
H_{loss}	predicted head loss between canal and vortex tube outlet	(m)
k_s	Total roughness height (m)	
k_u	Ratio u'_*/u_*	
L	length of vortex tube or tunnel section	(m)
L_{total}	total length of all vortex tubes in an installation, equal to local canal bed width	(m)
m	A coefficient in Ackers and White formulae	

List of symbols continued

n	channel roughness value in Manning's equation (also a coefficient in Ackers and White formulae in Appendix 2)	
N	number of tubes in a vortex tube design or tunnels at a certain section of a tunnel extractor	
P_{pl}	proportion of size fraction which passes the extractor	
P_{d5}	proportion of bed material downstream of extractor consisting of the D_5 size fraction upstream of extractor	
P_{di}	proportion of bed material downstream of extractor consisting of size fraction i	
P_{trN}	proportion of the total sediment load which consists of sediment from the D_N bed material size fraction	
q_*	Non-dimensional discharge	
Q	discharge	(m^3/s)
Q_c	canal discharge upstream of extractor	(m^3/s)
Q_{calc}	discharge calculated from Manning's equation	(m^3/s)
Q_e	total flow through extractor, and passing into escape channel	(m^3/s)
$Q_{Flushing}$	flushing discharge extracted from canal for a tunnel extractor	(m^3/s)
Q_T	discharge through each vortex tube or tunnel	(m^3/s)
r	hydraulic radius of channel cross-section, defined as area/wetted perimeter	(m)
r_n	new hydraulic radius in iterative method for depth prediction	(m)
R	extraction ratio, the proportion of the upstream flow extracted from the canal	(%)
R_{curve}	radius of curvature of canal bend	(m)
R_g	Grain Reynolds number	

List of symbols continued

R_{hd}	ratio of hydraulic radius to depth	
R_t	ratio of unblocked tunnel height, h_f, to tunnel width, b	
R_{trN}	transport rate of D_N size fraction in bed material relative to other size fractions (units not specified)	
S	energy slope in a channel	
S_g	specific gravity of the sediment, for quartz sand $S_g = 2.65$	
T	Temperature in degrees centigrade	
T_S	Transport stage parameter	
T_{tr}	total transport rate for all size fractions (in units of R_{tr})	
TE	trapping efficiency, the proportion of the upstream sediment load extracted from the canal	(%)
TE_{25}	trapping efficiency of extractor when R = 25%	(%)
TE_i	trapping efficiency of size fraction i	(%)
$\bar{u}$	mean velocity in a channel	(m/s)
$\bar{u}_e$	mean velocity at exit section of tunnel extractor	(m/s)
$\bar{u}_i$	mean velocity at upstream end of escape channel	(m/s)
u_*	Shear velocity	(m/s)
u_{*Cr}	Critical shear velocity	(m/s)
u'_*	Shear velocity related to grain roughness	(m/s)
V	mean velocity along tube axis in vortex tube	(m/s)
w	Fall velocity of particles	(m/s)
X_{AW}, X_{EH}	Total load sediment concentration from Ackers and White, Engelund and Hansen etc transport equations	(ppm)
X_b	Bed load transport (van Rijn formulae)	
X_c	mean sediment concentration entering the canal system	(ppm)

List of symbols continued

X_r	ratio of the sediment concentration that a canal system can transport to the concentration entering	
X_s	Suspended load concentration	
X_t	sediment transporting capacity of the canal system	(ppm)
X_T	sediment concentration in flow through extractor tunnels	(ppm)
Y	Entrainment function	
Z_y	Suspension number	
Z'_y	Modified suspension number	
α	factor used in linear interpolation between tables	
β	A factor in van Rijn formulae	
Δ	Bed form height	(m)
δ	Thickness of laminar sub-layer	
θ_{Cr}	Critical mobility parameter	
ν	kinematic viscosity of water	(m^2/s)
σ_S	Geometrical standard deviation of particle size	
τ_{*o}	Critical dimensionless shear stress	

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Tables *Tables associated with each section are contained in Volume II of the Design Manual*

Appendices *Appendices appear in Volume III of the Design Manual*

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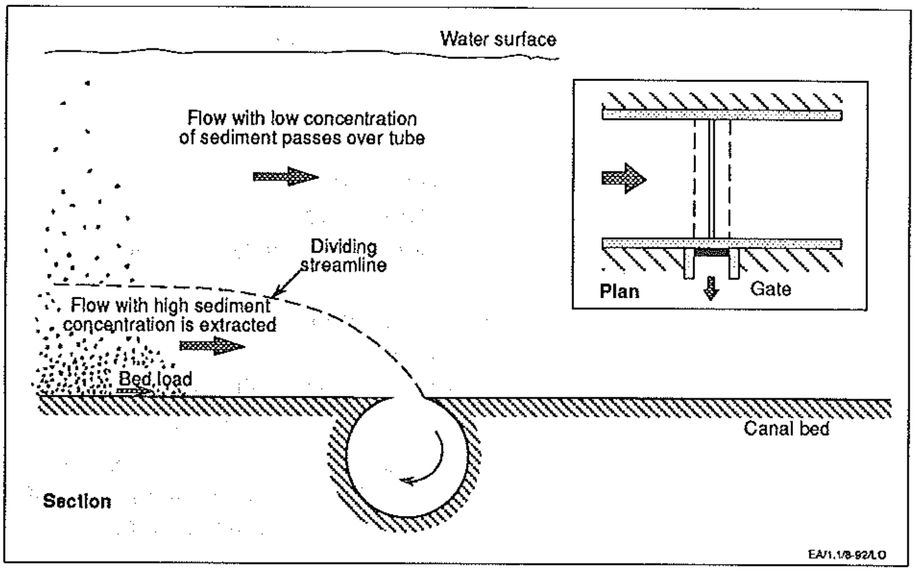


Figure 1.1 A vortex tube sediment extractor with one tube

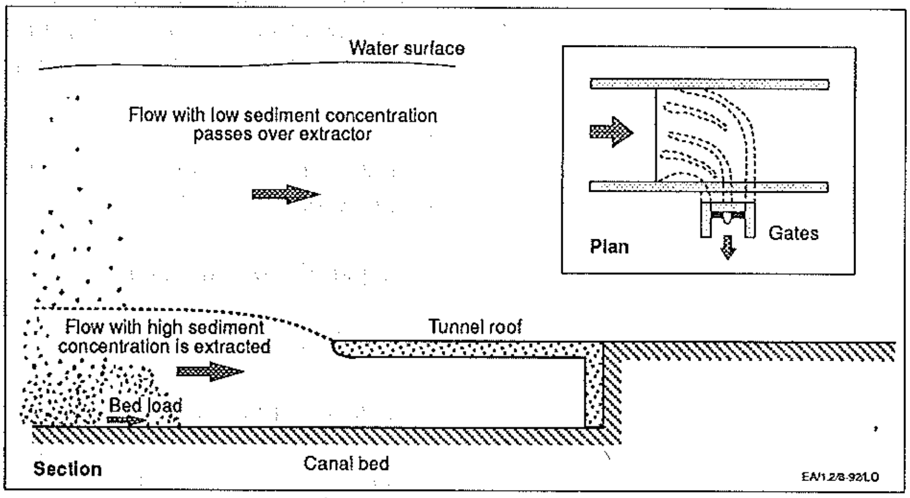


Figure 1.2 A tunnel sediment extractor

1 Introduction and how to use the manual

1.1 Canal Sediment Extractors

1.1.1 Description

The manual sets out methods for designing vortex tube and tunnel sediment extractors. Both devices function by separating, and then ejecting, the sediment laden bottom layer of flow in a canal. They are usually located in the head reach of canals where additional water can be diverted to operate the extractor, and head is available so that the extracted water and sediment can be conveyed back to the river.

The two types of extractor are shown in Figures 1.1 and 1.2. Water and sediment from the region close to the canal bed is diverted into the extractor, and taken out through one canal bank to an escape channel. The escape channel usually returns the water and sediment to the river, Figure 1.3.

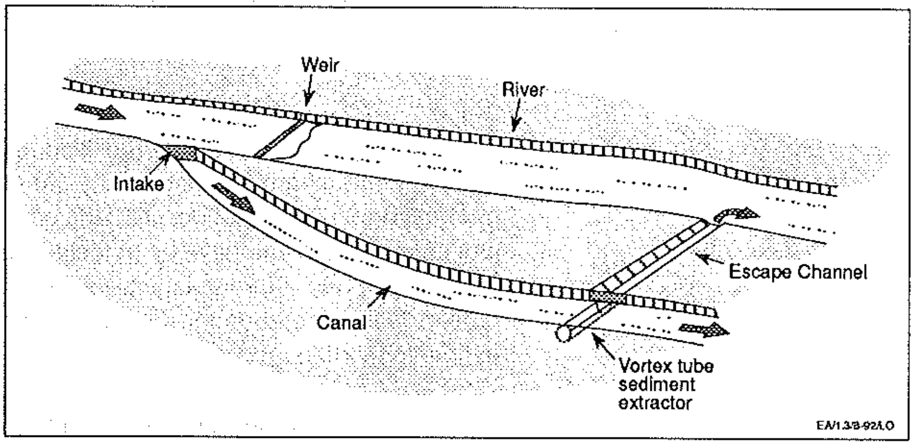


Figure 1.3 Typical layout for a sediment extractor

By extracting water from the near-bed zone a substantial proportion of the bed material sediments entering the canal can be removed, at the expense of between 10% and 20% of the canal discharge. The quantity of sediment that can be extracted depends mainly on the sediment sizes in transport, and the quantity of water that is diverted through the extractor. It also depends, but to a lesser extent, on other hydraulic parameters such as canal discharge and flow depth.

1.1.2 Applicability

Vortex tube or tunnel sediment extractors are not a universal solution for canal sedimentation problems. In many applications other, probably more expensive structures will be more appropriate, for example sluiced settling basins. The following conditions usually have to be satisfied if a vortex tube or tunnel extractor is to be used.

(i) The total discharge required to operate the extractor, and to meet the irrigation demand must be available, and be capable of being diverted to the canal head reach. The discharge required to operate the extractor will usually be between 10% and 20% of the canal full supply discharge. If the additional discharge required to operate an extractor cannot be diverted from the river then the discharge for irrigation has to be reduced.

(ii) There must be a head difference between the canal headreach and the river at the escape channel outfall in order to operate the extractor and to convey the extracted water and sediment back to the river. Thus vortex tube or tunnel sediment extractors can usually only be used where there is a weir in the river at the offtake.

(iii) The sediment trapping efficiency for vortex tube and tunnel extractors reduces as the sediment to be extracted becomes smaller. Between 40% and 80% of the bed material sediments moving in the canal will usually be extracted. If larger sediment trapping efficiencies are required, then vortex tube or tunnel type extractors will probably not be suitable, unless used with some other means of sediment control. Very fine sediments (silts and clays) are distributed uniformly throughout the depth, and the sediment trapping efficiency for fine sediments will be very low. Vortex tube and tunnel sediment extractors are therefore not suitable for extracting fine sediments.

1.1.3 HR Design methods

The design and performance prediction methods presented in this manual are the result of research carried out by the ODU over a number of years. They are based on theoretical descriptions of the sediment transport and hydraulic process involved, and have been tested with field data collected at operational structures. This approach contrasts with the empirical basis of many of the earlier design methods for sediment extractors, which were often based on hydraulic model studies.

The advantage of the methods described here is that the sediment trapping efficiency, principal dimensions and head loss etc. of an extractor can be predicted at the design stage, using tables or microcomputer programs. This enables the designer to check that an extractor will provide a feasible solution to a sediment problem, and to match the performance of the extractor to the requirement at a particular site.

Only a very brief summary of the design theories that are used is presented in the manual, reports and papers describing the theoretical framework underlying the methods, and the field measurements that have been used to verify them are listed in Chapter 11.

1.1.4 Choice of structure

The differences between vortex tubes and tunnel sediment extractors lie in the method by which the bed layer of the flow is extracted. Both types of structure would produce a very similar trapping efficiency when placed at the same location. For this reason the applicability of an extractor of either type is assessed first and a suitable location selected before the choice between vortex tubes or tunnels is considered.

1.1.5 Calculations and DACSE microcomputer software

Some of the calculations required in setting a design for a sediment extractor are very complex, and would normally be performed on a computer. In order to ensure that the manual is useful to engineers without access to computing facilities, design tables have been included so that designs can be prepared using the tables and a calculator.

However, the task of designing a sediment extractor is lengthy even with the help of the design tables, and so a set of microcomputer programs has been produced in conjunction with the manual. The programs are incorporated into the software package "DACSE" (Design Analysis for Canal Sediment Extractors), which runs on IBM compatible microcomputers.

TABLE

DACSE

It is important to stress that the DACSE software package is not an expert system which replaces the need for the manual. It is a set of programs which assist the user of the manual, and can be obtained from HR Wallingford.

Throughout the manual the user is given a choice of either hand calculations and design tables, or use of DACSE. **Markings have been included in the margin to highlight those parts of the text which apply only to users of the tables and those parts which apply only to users of DACSE. Appendix 1, the examples, is split into two self-contained sets, one set for DACSE users and the other for users of the design tables.**

Tables associated with each section are contained in Volume II of the Design Manual

1.2 How to use the manual

The design procedures are presented in self contained sections, centered around the various aspects of the design task. The arrangement of the sections generally follows the order in which the tasks would be carried out.

For simplicity the procedures have been presented for typical operating conditions in the canal and for averaged sediment loads. Once a workable design has been developed, the procedure could be repeated for the range of likely operating conditions that are expected, and engineering judgement used to adjust the extractor dimensions or operating discharges as required. A preliminary set of operating rules, such as the minimum canal discharge at which the extractor can be operated, can also be prepared.

As in any design task, compromises will probably be necessary, and these will require the repetition of some or all of the steps shown above, as a suitable design is evolved.

A list of the data needed to carry out the calculations is included in each chapter. However, for many calculations there are a number of options, depending on what data are available. Data requirements, and the preliminary calculations that may be necessary to derive sediment size gradings and hydraulic data etc. are discussed in more detail in Appendices 3 and 4, which should be consulted before calculations are attempted.

Appendices appear in Volume III of the Design Manual

We recommend that the examples given in Appendix 1 are worked through before the manual is used to design a sediment extractor. The examples present additional detailed information, and discuss some of the more practical aspects of locating and operating a sediment extractor. DACSE users should familiarise themselves with use of the programs by following the tutorials in the "DACSE User Guide".

Note: to avoid confusion in writing the equations, an asterisk (*) has been used throughout the manual to indicate "multiplied by".

2 *Definitions, symbols and data*

2.1 Performance parameters for sediment extractors

The performance of vortex tube and tunnel sediment extractors can be specified by the relationship between two parameters. These are:

Sediment trapping efficiency, TE, defined as:

$$\frac{\text{Quantity of sediment extracted from canal}}{\text{Quantity of sediment being carried by the canal upstream}} * 100\%$$

Extraction ratio, R, defined as:

$$\frac{\text{Discharge diverted through extractor}}{\text{Canal discharge upstream from extractor}} * 100\%$$

2.2 Sediment Transport Definitions

The sediment transported by a river and diverted into a canal can be divided into three classes, depending on the mode of sediment transport (See Figure 2.1).

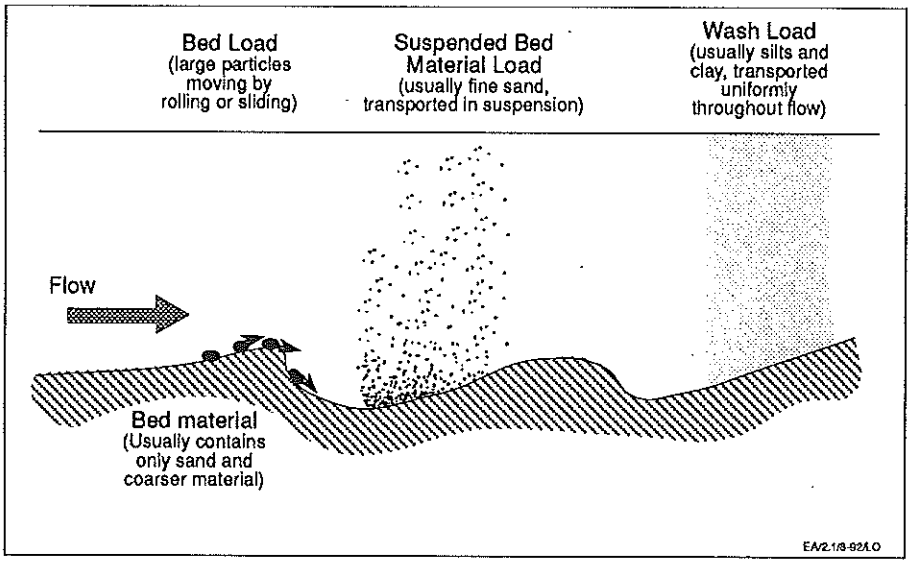


Figure 2.1 Sediment transport definitions

Bed Load - The relatively coarse sediment that moves by rolling or sliding, in almost constant contact with the bed is defined as bed load. By using an appropriately designed intake, bed load in a river can often be prevented from entering an irrigation offtake. Bed load usually represents less than 15% of the sand sized and larger sediment in transport.

Suspended Bed Material Load - Sediment, usually fine sand, that is present in the channel bed but is transported in suspension, is termed suspended bed material load. Suspended bed material usually forms the bulk of the sediments that enter and then settle in conventionally designed canal systems.

Wash Load - We define wash load as those fine sediments (usually silts and clays) which are transported in suspension but are not present in appreciable quantities in the bed. In rivers and conventionally designed canals the wash load is uniformly distributed in the flow. Wash load is often passed through canal systems and onto the fields.

In the manual, washload is defined as sediments smaller than 63 microns (0.063mm), that is the silt and clay size fractions. Wash load is excluded in all calculations.

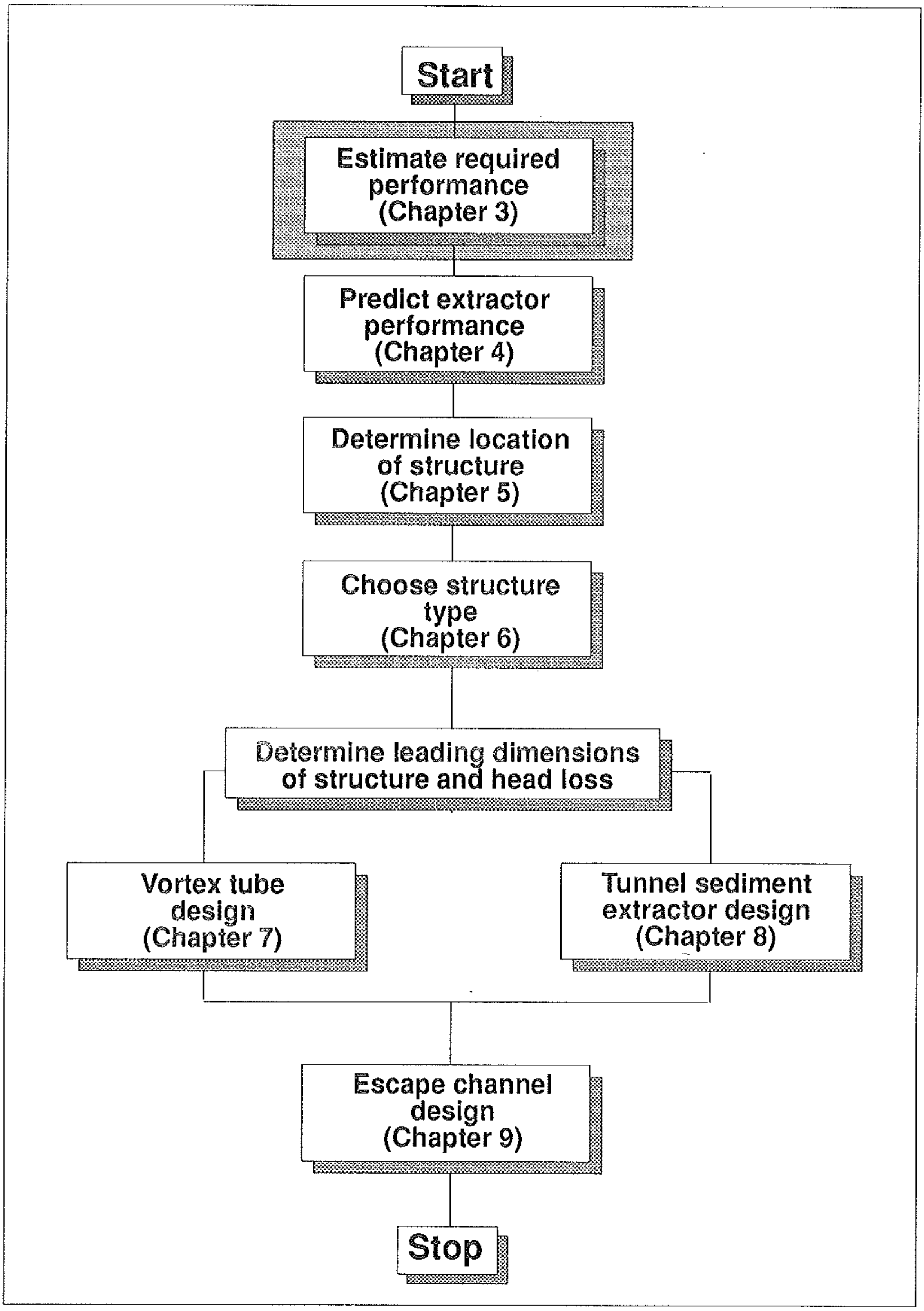
In addition to these definitions the term "suspended sediment size" is used in many places in the manual. Strictly this should be "The size of the material in transport which originates in the bed"; however, for canals there is only a slight distinction between the terms because the suspended bed material load usually dominates the bed material in transport.

2.3 Symbols

Symbols are defined in the text, and are also listed at the front of the manual.

2.4 Data requirements

A summary of the data required to carry out the calculation is included at the start of each chapter. A more comprehensive discussion of data requirements is presented in Appendix 4.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3 Estimating required performance

3.1 Introduction

The required sediment trapping efficiency is estimated from the ratio X_r of the sediment concentration that can be transported by the canal, to the sediment concentration that enters the canal (Figure 3.1).

$$X_r = \frac{\text{Sediment concentration that can be transported}}{\text{Sediment concentration entering the canal}}$$

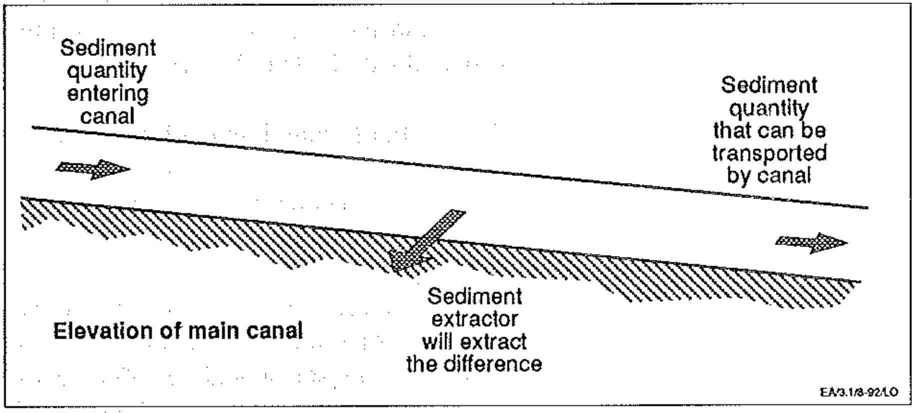


Figure 3.1 Required performance of a sediment extractor

Approximate methods for estimating X_r, based on the use of alluvial friction and sediment transport predictors are presented in this chapter, however these estimates could be subject to quite large margins of error. (The errors that can be expected when sediment concentrations have to be predicted are discussed in Appendix 2). If it is possible then field measurements of the sediment concentrations entering and transported by canal systems where extractors are to be considered are recommended. Even if a full programme of field data collection is not feasible, limited measurements can be of great value as they will help in the selection of the most appropriate alluvial friction and sediment transport predictors.

3.2 Transporting capacity of a canal system

The concentration of sediments that can be transported by a channel is calculated from its depth and the other hydraulic parameters such as velocity and slope, and from one or more "representative" bed sediment sizes using a sediment transport equation. It will usually be necessary to use an alluvial friction predictor to estimate the depth of flow in a canal at its design discharge before a sediment transport calculation can be carried out.

When sediment transport calculations are applied to conditions in an irrigation canal system it is often found that the smaller canals have a lower transporting capacity than the main canal. The sediment load passing a sediment control device cannot then be matched to the transporting capacity throughout the canal network. Possibly, engineering judgement must be used to select the size of canal for which the transporting capacity is assessed. The examples in Appendix 1 include calculations where the predicted sediment load passing an extractor is matched to the main canal's transporting capacity (Example 1) and a secondary canal transporting capacity (Example 2).

Sediment transport equations and alluvial friction predictors are listed in a common notation in Appendix 2, and use of the methods is illustrated in Appendix 1. As the different methods can give significantly different predictions a combination of friction and transport methods should be selected which provides the best prediction of measured sediment transport rates in existing canals, or for similar canals in the same region if the scheme has not been constructed. If the field data needed to make this choice are not available then the van Rijn friction and Engelund and Hansen transport predictors should be selected. This combination of methods performed best when the methods were tested against a set of measured canal data. (Appendix 2, Section A2.14).

If the canal system has not been constructed then the canal's bed material size grading must also be predicted to enable the calculations to be made. The prediction can be made using DACSE, or by undertaking the calculations presented in Appendix 3, Section A3.2.

If the canal system is in existence then bed material samples can be collected and size graded; the mean of *at least* five samples (preferably more) should be used. Samples should be collected from the centre of the canal bed at the point where sediment transporting capacity is being assessed.

3.3 Sediment concentrations entering an offtake

3.3.1 Existing offtake

The sediment concentrations entering an existing offtake can be measured, preferably using the pump sampling technique, described in Atkinson (1989). Measurements should be repeated a number of times to cover a representative range of river and canal flows.

If measured data are unavailable then the "mean" sediment concentration entering an existing offtake can be estimated using a sediment transport equation, provided the slopes in the upstream reaches of the canal system have steepened to an "equilibrium" slope. (After a canal has been operated for a few years the bed may have adjusted to the incoming sediment loads so that, while bed level fluctuations might still occur, no further rising trend is observed. The average bed slope derived from those bed levels will then be approximately the same as the average water surface slope, this is the "equilibrium" slope.) The sediment transport predictor used to estimate the transporting capacity under design conditions should be used for this calculation, together with discharge records, water level records, canal survey data and bed sediment sizes collected from the site.

The above method is not valid if the canal reaches concerned are being regularly desilted. However, desilting records will then be of use in estimating the sediment input to the canal, see Figure 3.2.

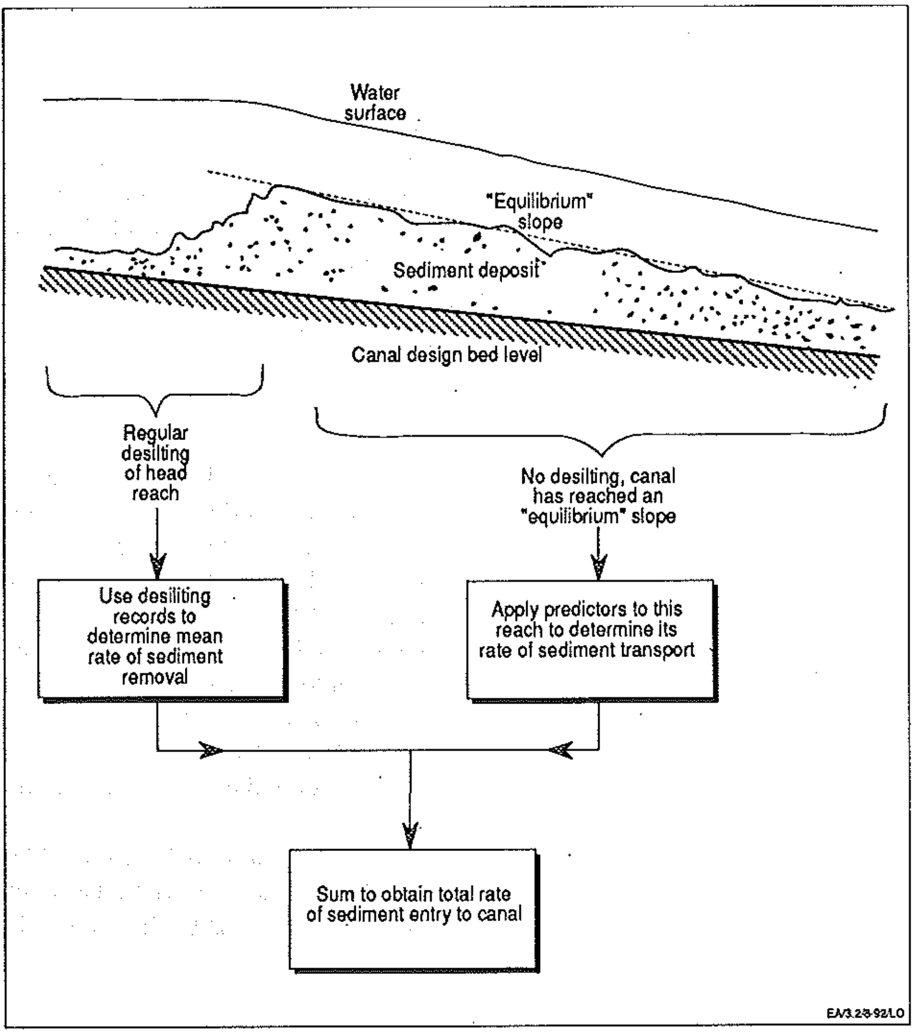


Figure 3.2 **Example of combined use of desilting records and an "equilibrium" slope to determine sediment entry to a canal**

3.3.2 Offtake before construction

Estimating the sediment concentration that will enter an offtake before it is constructed is difficult. It will be influenced by river conditions, the design and siting of the offtake, the performance of any sediment exclusion features that are to be incorporated, and the way in which the intake is to be operated at times when high sediment concentrations are transported in the river.

As a first approximation, the suspended bed material sediment concentrations that will enter the offtake can be taken to be the same as those transported in the river. A calculation procedure based on this assumption is described in Appendix 1, Example 1.

The proportion of the river's bed load entering a canal will also depend on offtake configuration, and could be larger or smaller than the proportion of the river flow abstracted. However, a well designed offtake will exclude bed load from the canal.

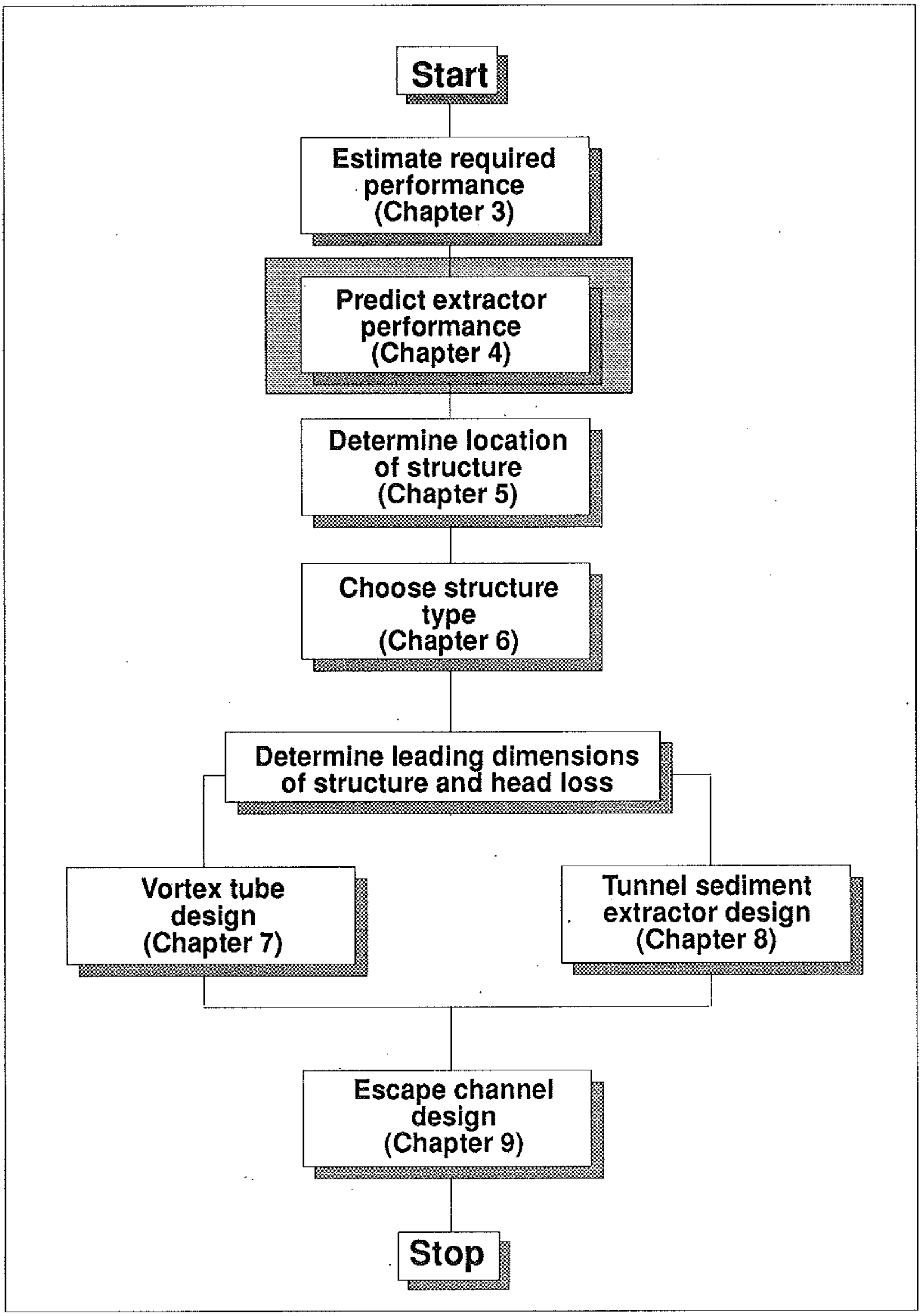
3.4 Seasonal averaging

In many river systems, most of the sediment is transported, and thus enters irrigation offtakes, during a more or less well defined wet season. At other times very little sediment enters canals. If this is the case then a sediment extractor would only be operated during the "sediment season", and the mean sediment concentration should be calculated on a seasonal basis. If there are significant variations in canal discharge as well as in the sediment concentrations then the sediment concentrations entering the canal should be weighted by canal discharge to assemble a mean "discharge weighted" sediment concentration. An example of this kind of calculation is included in Appendix 1, Example 1.

3.5 Interpreting the ratio X_r

X_r is the ratio of the sediment concentration that can be transported by the main canal system and the mean incoming sediment concentration, and is estimated by procedures described in the previous sections. If X_r is small, say less than 0.15, then a very high trapping efficiency will be required, this is unlikely to be achieved with a sediment extractor unless the sediments are very coarse. On the other hand if X_r is large, say more than 0.8, only a small degree of sediment control is necessary, and occasional desilting of the canal could be more cost effective than building a sediment extractor. Thus if X_r is larger than 0.8, a sediment extractor is in most cases inappropriate, and there is no point in proceeding any further with the design procedure.

If X_r is less than 0.15 an extractor could well be useful in providing a partial solution to the sediment problem. However other sediment control structures, for example settling basins, should also be considered.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4 Predicting extractor performance

4.1 Introduction

The method presented in this section is used to predict the sediment trapping efficiency of a vortex tube or tunnel sediment extractor. A prediction of sediment trapping efficiency is used initially to assess the feasibility of a sediment extractor at the site in question, and later to determine the extractor discharge needed to achieve the required sediment trapping efficiency. The performance of the extractor is determined by the relationship between two parameters, water extraction ratio and sediment trapping efficiency, both defined in Chapter 2.

The procedure is based on the trapping efficiency model described by Sanmuganathan (1976), with the modifications described by Atkinson, (1987). The method, which has been extensively field tested (Atkinson, 1987), uses the following computational steps. Firstly the position of the dividing streamline, Figure 4.1, which separates the flow and sediment entering the extractor from the flow and sediment passing over the extractor, is estimated. Then the proportion of the total sediment load below the dividing streamline is calculated from theoretical sediment concentration and velocity profiles. This ratio is the sediment trapping efficiency.

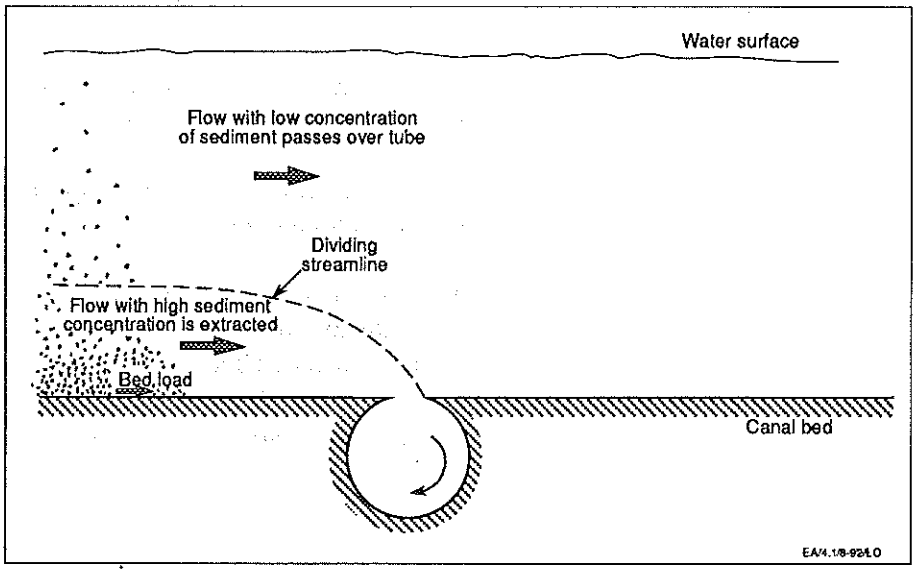


Figure 4.1 A vortex tube sediment extractor with one tube

4.2 Data required

The following data are required in order to carry out a trapping efficiency prediction, see Figure 4.2. More detailed information on data requirements is given in Appendix 4.

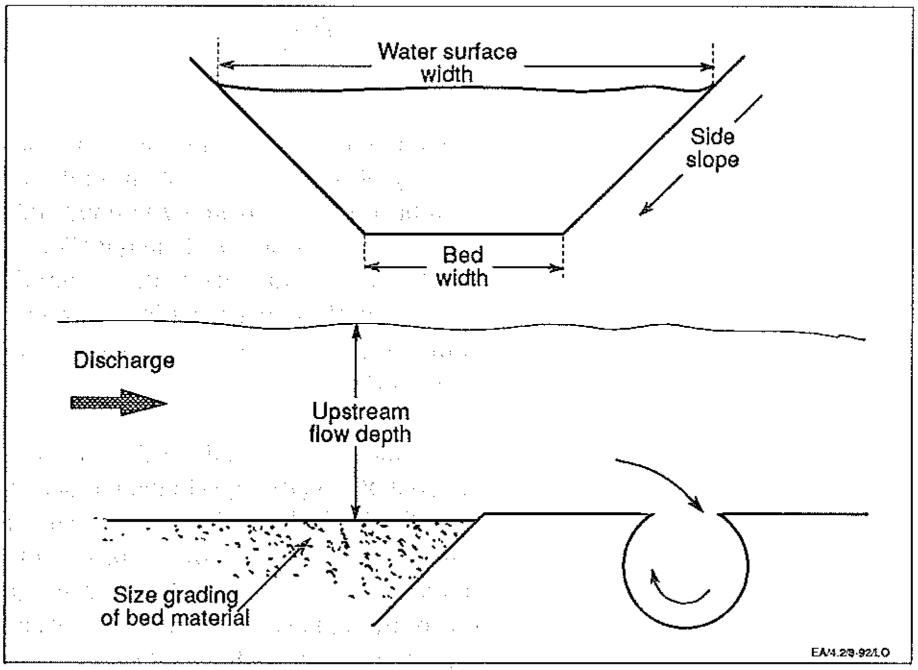


Figure 4.2 Data required for calculation of trapping efficiency

- A cumulative size grading curve for the canal bed material at the proposed extractor location, Figure 4.3.
- The mean width and typical operating discharge in the canal reach upstream from the extractor.
- The flow depth and water surface slope in the canal reach upstream from the extractor. (Note that because there will be some sediment deposition in the canal reach between the intake and the extractor, the flow depth and slope upstream from the extractor will probably not be the same as the design flow depth and slope for the canal).

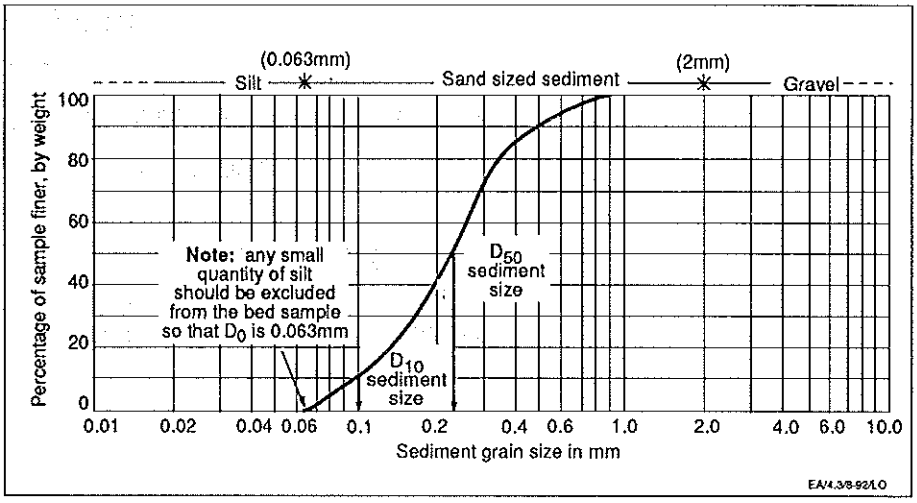


Figure 4.3 Example of a bed material size grading

The sediment concentration ratio X_r (calculated in Chapter 3) is required to determine a suitable extraction ratio.

4.3 Initial prediction of extractor performance

DACSE

Using DACSE:
Select the *Trapping Efficiency* option on the main menu and enter the canal data requested. In addition to the parameters listed in 4.2 above the program requires water temperature and S_g the specific gravity of the sediment (S_g = 2.65 can be used in the absence of data). Run the program with extraction ratios of 5%, 10%, 15%, 20% and 25%, and tabulate the resulting trapping efficiencies.

TABLE

Using the tables:
Three sets of tables are included in Volume II. The first set gives trapping efficiency predictions from the bed material size grading, the second set uses the suspended material size grading, and the third set represents uniform sediment grading.

Actual trapping efficiency predictions are based on the size grading curve of the suspended bed material (Figure 4.3), with an allowance for bed load. However it is more convenient for the user to have the bed sediment sizes as an input in the trapping efficiency prediction. Thus the first set of tables is used unless the D_{50} of the bed material size is greater than 0.35 mm, or the ratio D_{50}/D_{10} is greater than 2.5, these being the largest values covered by that set.

It is not feasible to prepare the very large number of tables based on bed sediment sizes required to cover conditions outside this range. Thus if the D size or the D_{50}/D_{10} ratio are too large, then the second set of tables has to be used. A preliminary calculation is necessary to estimate the size grading curve for suspended sediments from the bed material, using the method given in Appendix 3, Section A3.1.

The third set of tables is used later in this chapter (Section 4.5.2).

The steps required for calculating trapping efficiency from the tables are:

(i) Calculate the sediment size ratio for the canal bed material,

size ratio = D_{50}/D_{10}

where:

D_{50} = size at which 50% of a sediment sample is finer

D_{10} = size at which 10% of a sediment sample is finer (see Fig 4.3)

(ii) Calculate the discharge per metre width (m^2/s) of the flow upstream of the extractor:

$$\text{discharge per m width} = \frac{\text{canal discharge } (m^3/s)}{\text{mean width } (m)}$$

TABLE

(iii) Calculate the Froude number, Fr, of the flow upstream of the extractor:

$$Fr = \frac{\text{mean velocity}}{\sqrt{g * \text{depth}}}$$

where:

$$\text{mean velocity} = \frac{\text{canal discharge } (m^3/s)}{\text{mean width } (m) * \text{depth } (m)}$$

and $g = 9.81 m/s^2$

(iv) Use the tables for either bed material sediment or suspended material sediment to read off the predicted trapping efficiency of an extractor for each of the extraction ratios given (5%, 10%, 15%, 20% and 25%). A table of predicted trapping efficiency against extraction ratio should be prepared. Initially use the design table for the nearest D_{50} and sediment size ratio to obtain a first estimate for trapping efficiency. If a more precise prediction of trapping efficiency is required then linear interpolation within and between tables may be necessary. (Linear interpolation is demonstrated at the start of the tables).

4.4 Assessing extractor performance

The required sediment trapping efficiency is approximately:

$$\text{required efficiency} = (1 - X_r) * 100\%$$

where:

$$X_r = \frac{\text{Sediment concentration which can be transported}}{\text{Sediment concentration entering canal}}$$

The required trapping efficiency usually reduces as the extraction ratio increases, due to the extractor's effect in reducing the sediment sizes downstream of the extractor. However, if the required trapping efficiency is considerably more than the predicted trapping efficiency at an acceptable extraction ratio, then a sediment extractor will not solve the problem. If this is the case then:

- consider another (probably more expensive) means of sediment control, such as a sluiced settling basin, or
- consider the economics of using an extractor to achieve only partial sediment control.

If an extractor appears feasible, then proceed with setting the extractor discharge.

4.5 Setting extractor discharge

4.5.1 Method

Extractor discharge is set to obtain a trapping efficiency which reduces the sediment concentrations to the transporting capacity of the canal system. A typical example of the variation in trapping efficiency with water extraction ratio is shown in Figure 4.4.

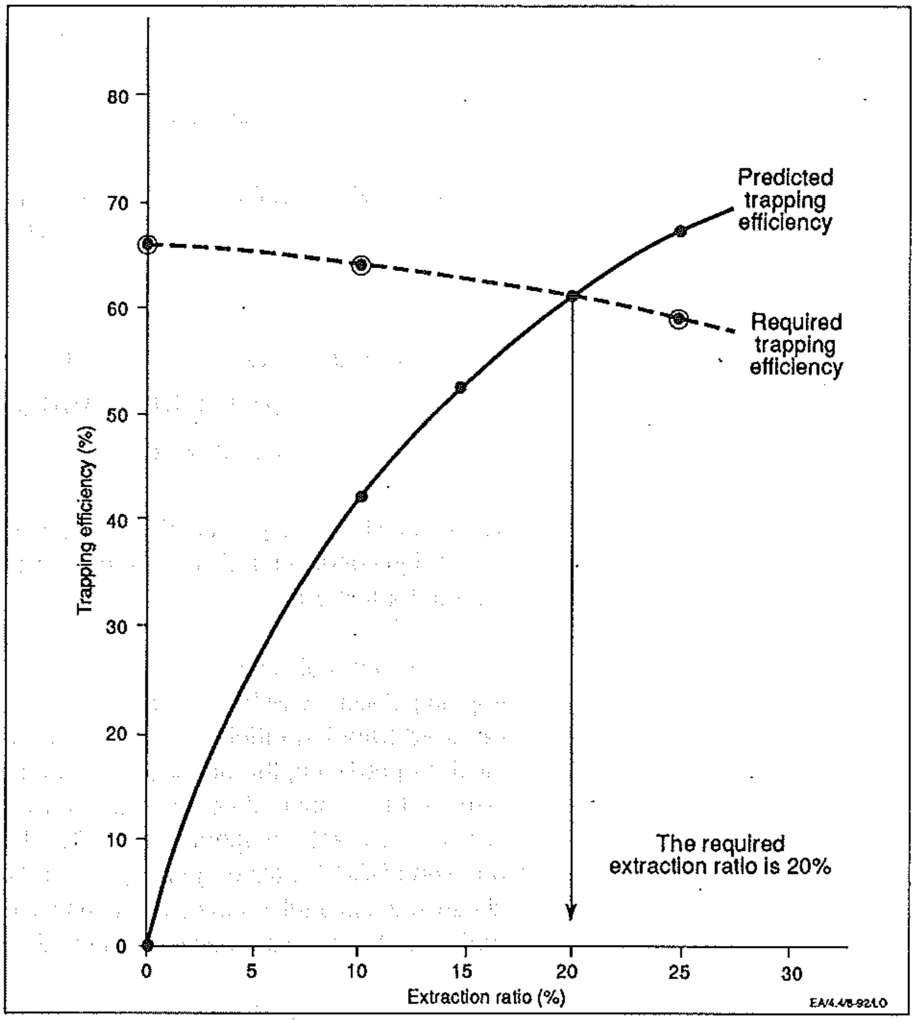


Figure 4.4 Example of the combined plot of required and predicted trapping efficiency to set required extraction ratio

The trapping efficiency that is required tends to reduce as water extraction ratio is increased. This is because the sediment sizes passing over the extractor become finer as more water and sediment are extracted, and hence the sizes in the bed material downstream from the extractor become finer than in the bed material upstream from the extractor. (An example of size grading curves upstream and downstream from an extractor is shown in Figure 4.5). The reduced sediment sizes downstream from an extractor enables the canal to transport larger sediment concentrations at the design slope, and thus to a reduction in the trapping efficiency that is required. This effect is shown in the "required trapping efficiency" curve in Figure 4.4.

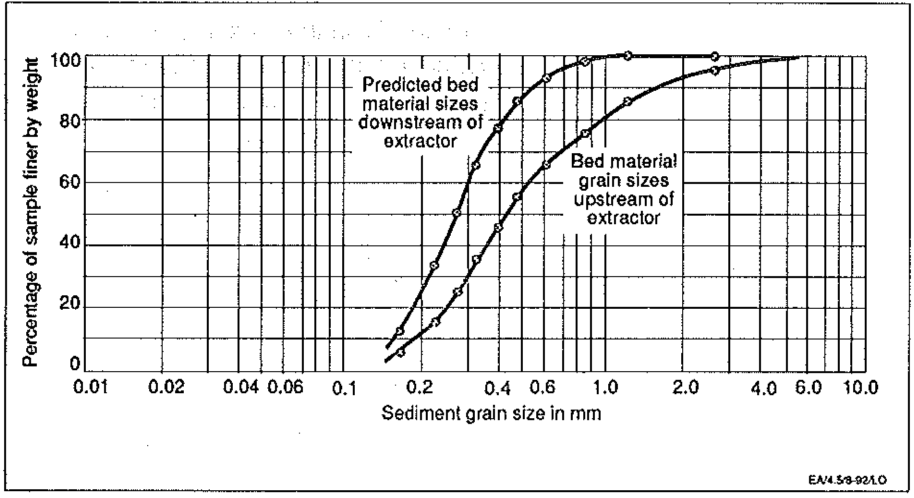


Figure 4.5 **Example of size grading of bed material upstream and downstream of extractor**

The point where the predicted and required trapping efficiency curves cross is the design condition and so sets the extraction ratio, in the example shown in Figure 4.4 it is 20%.

Two sets of calculations have to be carried out, firstly the variation in predicted trapping efficiency with water extraction ratio, and secondly the variation in the required trapping efficiency with extraction ratio. The second calculation involves predicting the effect of the water extractor in reducing the sediment sizes in the canal bed downstream from the extractor, and recalculating the canal's sediment transporting capacity. These computations are best carried out using DACSE, although lengthy hand calculations are possible. In many circumstances a full hand calculation would not be justified. This is discussed further in the following section, and in the examples.

4.5.2 Computations

DACSE

Using DACSE
The following computations are carried out for a suitable range of water extraction ratio, say 10%, 15%, 20% and 25%.

(a) If additional water is to be diverted to the canal to operate the extractor new canal discharges have to be calculated for each water extraction ratio. Flow depths for the new discharges are then calculated using the *Canal Depth and Slope* option in DACSE if prediction is necessary, or Manning's equation if data are available (see Appendix 4, Section A4.7).

(b) A trapping efficiency calculation is carried out for each of the selected water extraction ratios, using the *Trapping Efficiency* option in DACSE. The bed material size grading in the canal downstream from the extractor is computed and stored by the *Trapping Efficiency* program, and thus each trapping efficiency calculation should be followed by a transporting capacity computation. The *Alluvial Friction Calculation* and the *Sediment Transport Calculation* options in DACSE are used.

DACSE

(c) The required trapping efficiency for each extraction ratio can now be calculated from the new transporting capacities, and plotted on a graph of trapping efficiency against extraction ratio:

$$\text{Required efficiency} = 100 - \frac{(100 - R)\, X_t}{X_c}$$

where:

X_t is the sediment transporting capacity of the canal system downstream of the extractor in ppm

and

X_c is the annual or seasonal mean sediment concentration in the canal upstream of the extractor in ppm.

(d) The predicted trapping efficiency is plotted on the same graph, and the operating water extraction ratio required to achieve the target sediment trapping efficiency is read from the graph where the two curves intersect, (see Figure 4.4).

Using the tables:
The full procedure for setting the extractor discharge using tables and hand calculations is lengthy, and will only be justified where the calculations are based on reliable data. For example, if the canal has not been constructed, both the incoming mean sediment concentration, and the bed material size grading have to estimated, and these procedures are based on many assumptions. In these circumstances the accuracy of the predictions will not justify the effort involved in carrying out the full hand calculation and a simpler procedure set out below is used:

TABLE

(a) If additional water is to be diverted to the canal to operate the extractor, new canal discharges have to be calculated for a range of water extraction ratios. Flow depths for each of the new discharges are then calculated using the method set out in Appendix 4, Section A4.7.

(b) Plot a graph of predicted trapping efficiency as a function of extraction ratio for extraction ratios of 0, 5%, 10%, 15% and 25%. Trapping efficiency predictions are obtained from the Tables 4.1 (a) to 4.7 (d), for actual, rather than the closest tabulated conditions. Use linear interpolation, as explained in the example at the start of the tables.

(If the D_{50} of the bed material is greater than 0.35mm, or if the ratio D_{50}/D_{10} is larger than 2.5, then the suspended material size grading has to be derived from the bed material grading, using the method given in Appendix 3, and then Tables 4.8 (a) to 4.13 (f) are used to predict trapping efficiency).

(c) Plot on the same graph the trapping efficiency required at a very small, (taken as zero), extraction ratio:

required efficiency = $(1 - X_r) * 100$

X_r is defined in Section 4.4

The extraction ratio that provides a sediment trapping efficiency closest to that derived in step(c) can be selected as the design condition. Alternatively, the design trapping efficiency can be set at a little less than that estimated in step(c) above, because of the effect of the extractor in reducing downstream sediment sizes.

If it is justified then the additional calculations described below can be carried out to quantify this effect. The cases where this might be justified are discussed in the examples. As the calculations are lengthy they should be carried out for only two values of water extraction ratio, say 10% and 25%. Repeat steps (d) to (i) for each extraction ratio. The procedure is demonstrated in Example 2.

(d) Plot on a separate graph, sediment trapping efficiency as a function of bed material grain size for the range of sizes found in the bed, covering the range D_5 to D_{95}.

The graph should be prepared using Tables 4.14(a) to 4.14(o), which are for uniform sediment sizes.

(e) For each of the canal bed material sizes D_5, D_{15}, D_{25}, D_{35} ...... to D_{95} make a table of the proportion of the size fraction which passes the extractor, P_{pi}:

$P_{pi} = 1.0 - TE_i/100$

where:

TE_i is read from the graph in step (d). Here suffix i refers to the size fraction: $_{5}$, $_{15}$, $_{25}$ etc.

(f) Sum the proportions P_{pi} and divide each proportion by this sum. This gives the quantity in each size fraction as a proportion of the total for the bed material downstream of the extractor. These new proportions, P_{d5} ....P_{d95}, should be tabulated in the same table as in step (e).

(g) Tabulate and plot the sediment size grading curve of the bed material downstream of the extractor. The steps are as follows:

The D_5 size upstream (in mm) becomes the D_N size downstream where:

$$N = 100\left(\frac{1}{2} P_{d5}\right)$$

The D_{15} size upstream becomes the D_N size downstream where

$$N = 100\left(P_{d5} + \frac{1}{2} P_{d15}\right)$$

The D_{25} size upstream becomes the D_N size downstream where

$$N = 100\left(P_{d5} + P_{d15} + \frac{1}{2} P_{d25}\right) \text{ and so on up to}$$

The D_{95} size upstream becomes the D_N size downstream where

$$N = 100\left(P_{d5} + P_{d15} + P_{d25} \ldots\ldots\ldots\ldots + P_{d85} + \frac{1}{2} P_{d95}\right)$$

An example of the table used in these calculations is given below.

Sample Calculation of Size Grading

TABLE

D_{size} upstream of extractor in bed material	Size in mm*	Proportion passing extractor (P_{pi})	Proportion of bed material downstream of extractor (P_{di})	Sediment grading curve of bed material down-stream of extractor * (N in D_N)
D_5	0.17	0.63	0.23	12
D_{15}	0.23	0.51	0.19	33
D_{25}	0.28	0.43	0.16	50
D_{35}	0.33	0.36	0.13	65
D_{45}	0.40	0.29	0.11	77
D_{55}	0.48	0.23	0.08	86
D_{65}	0.62	0.16	0.06	93
D_{75}	0.86	0.09	0.03	98
D_{85}	1.25	0.04	0.01	100
D_{95}	2.70	0.00	0.00	100
		2.74		

* These two columns are used to plot the size grading curve for the bed material downstream of the extractor, Figure 4.5.

(h) Re-calculate the sediment transporting capacities in the canal system downstream of the extractor using the new bed material grain sizes and, where appropriate, the new discharge which passes the extractor.

TABLE

(i) The required trapping efficiency for this extraction ratio can now be calculated, and plotted on the graph of trapping efficiency against extraction ratio:

$$\text{Required efficiency} = 100 - \frac{(100 - R)\,X_t}{X_c}$$

where:

X_t is the sediment transporting capacity of the canal system downstream of the extractor in ppm, as calculated in step (h),

and X_c is the annual or seasonal mean sediment concentration in the canal upstream of the sediment extractor in ppm.

(j) There now should be three points of required trapping efficiency on the trapping efficiency graph; at R = 0%, R = 10% and R = 25%, join them with a curve.

(k) The operating water extraction ratio required to achieve the target sediment trapping efficiency is read from the graph where the two curves intersect, (Figure 4.4).

4.6 Siting extractors in a flumed section

There is some evidence to suggest that siting an extractor in a short flumed section (Figure 4.6) may enhance its trapping efficiency. However, the effect cannot be reliably predicted, so a clear recommendation cannot be made.

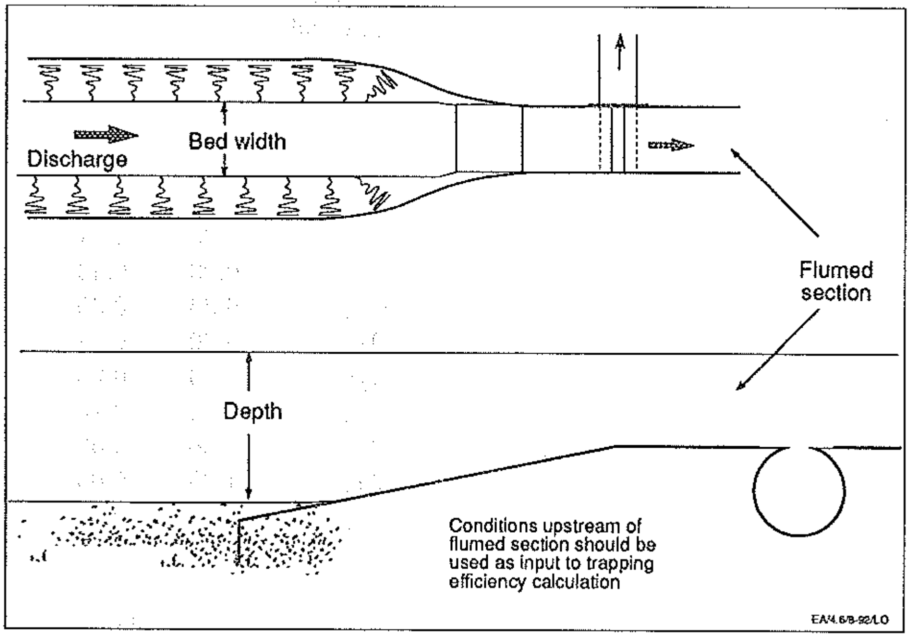


Figure 4.6 Example of an extractor sited in a flumed section

In some circumstances it is convenient to site an extractor in a flumed section. Trapping efficiency should then be predicted using conditions in the canal *upstream* of the flumed section.

4.7 Notes on the use of the tables

The tables for trapping efficiency prediction are presented in Volume II.The tables presented are for the conditions:

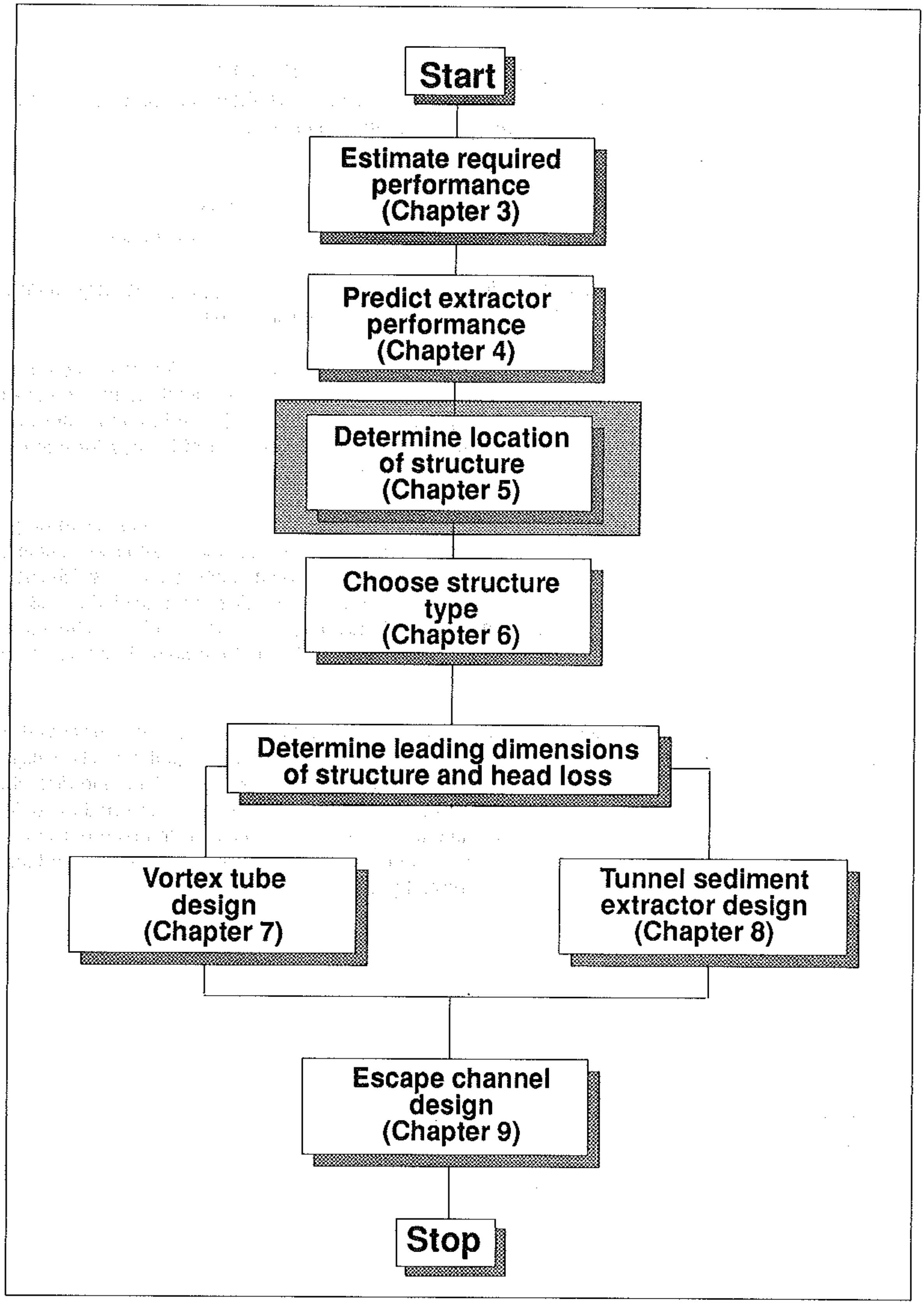
- Temperature = 20°C
- Specific gravity of sediment = 2.65
- Uniform extraction of water across the canal

If these conditions do not hold, then the trapping efficiency predictions can be adjusted using the following approximations:

(i) Temperature. Predicted trapping efficiencies increase with rising water temperature; use the approximate guide of a 3% increase in trapping efficiency for each 5°C rise in temperature above 20°C. Similarly a 3% drop in predicted efficiency for each 5°C drop in temperature below 20°C.

(ii) Specific gravity of sediment, S_g. The tables were prepared with a value of specific gravity of 2.65; most sand sized sediment has this value. However, S_g can be as high as 3.0, in which case add 4% to the predicted trapping efficiencies. Similarly if $S_g = 2.30$ subtract 5% from the predicted trapping efficiencies. The adjustment for intermediate values of S_g can be obtained from linear interpolation between these values.

(iii) Vortex tube sediment extractors do not extract water uniformly across the canal width, and the unequal extraction slightly reduces trapping efficiencies. For tubes with a length to diameter ratio of 6 or less, the effect is insignificant. If L/d is equal to 10, its maximum recommended value, then predicted trapping efficiencies from the tables should be reduced by 4%. If L/d = 8, reduce predicted efficiencies by 2%.


Start
Estimate required performance (Chapter 3)
Predict extractor performance (Chapter 4)
Determine location of structure (Chapter 5)
Choose structure type (Chapter 6)
Determine leading dimensions of structure and head loss
Vortex tube design (Chapter 7)
Tunnel sediment extractor design (Chapter 8)
Escape channel design (Chapter 9)
Stop

5 Extractor location and canal water levels

5.1 Introduction

Ideally an extractor should be located at the point downstream from the headworks where the turbulence created at the intake has decayed, and an equilibrium sediment cncentration profile in the vertical is established, Figure 5.1. If the extractor is located too close to the intake the sediment trapping efficiency will be reduced. On the other hand placing the extractor too far from the intake unnecessarily increases the distance between the intake and the extractor over which deposition will occur, which could result in unacceptably high water levels at the downstream side of the intake gates.

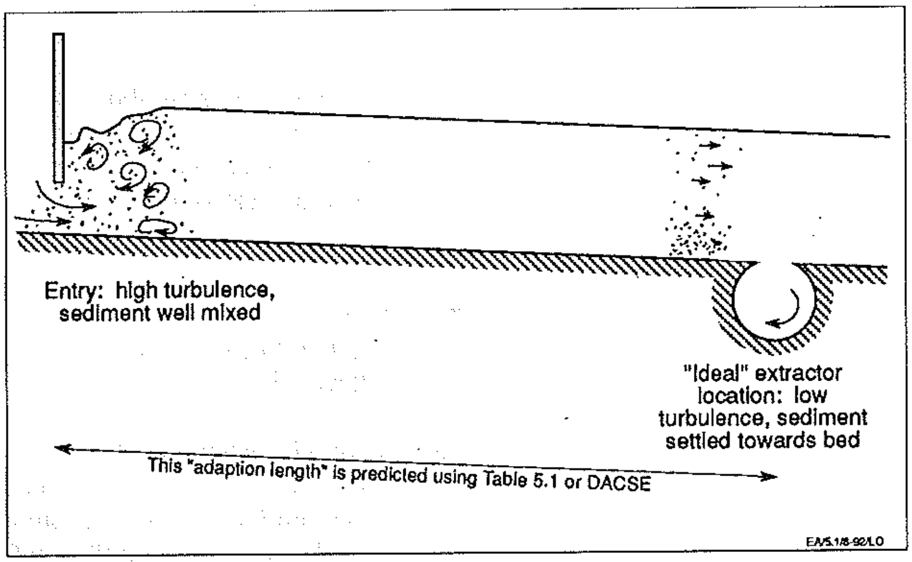


Figure 5.1 The "ideal" for sediment extractor location

The method for predicting the "ideal" location uses a computational model to solve the turbulent diffusion equation for suspended sediment, described in Atkinson (1986). The distance from the intake for an initially uniform sediment concentration profile to adapt to an "equilibrium" profile is predicted. Following UPIRI (1975) the predicted adaption lengths are increased by 50% to account for the additional turbulence generated at the intake. The prediction program is included in the DACSE package, adaption lengths are also tabulated in Table 5.1 as a function of sediment size and hydraulic parameters.

Adaption lengths are computed using a representative grain size, taken as the D_{50} size in suspension. However, because adaption length is dependent on the grain size predicted, adaption lengths can only give an approximate indication of the best extractor location.

5.2 Data required

The following data are required in order to estimate the distance downstream from an intake at which an "equilibrium" sediment concentration profile will be established. More detailed information on data requirements is given in Appendix 4.

- A cumlative size grading curve for the suspended bed material entering the canal. (If measured size gradings curves are not available, then the suspended size grading can be estimated from the canal bed material size grading, see Appendix 3, Section A3.1. The DACSE trapping efficiency program provides the D_{50} sediment size in transport, and so DACSE users will not have to carry out this calculation).

- For users of the tables: the mean width, typical operating discharge and depth in the canal reach upstream from the extractor.

- For DACSE users: the flow depth, mean velocity and water surface slope at typical operating conditions in the canal reach upstream from the extractor.

(Note that because there will be some sediment deposition in the canal reach between the intake and the extractor, the flow depth and slope upstream from the extractor will not be the same as the design depth and slope for the canal, see Appendix 4).

5.3 Procedure for predicting adaption length

DACSE

Using DACSE:
Select the option *Adaption Length Calculation* from the main menu, and enter the data requested.

If the trapping efficiency program has been run, the D_{50} sediment size in transport will already be entered on the input screen. The velocity, slope and the flow depth are for conditions upstream from the extractor; if they have been computed by the *Canal Depth and Slope* option, they too will already be available in the input data screen.

TABLE

Using the table:
The adaption length table is used by following these steps:

(i) Determine the D_{50} sediment diameter from the cumulative size grading curve for suspended bed material sediment entering the canal.

Where:

D_{50} = size at which 50% of the suspended bed material sediment is finer (mm)

(ii) Calculate the discharge per metre width (m^2/s) for the flow in the headreach.

Where:

$$\text{discharge per m width} = \frac{\text{canal discharge } (m^3/s)}{\text{mean width } (m)}$$

TABLE

(iii) Calculate the Froude number, Fr, for the flow in the canal head reach:

$$\mathrm{Fr} = \frac{\text{mean velocity}}{\sqrt{g * \text{depth}}}$$

$$\text{mean velocity} = \frac{\text{canal discharge } (m^3/s)}{\text{mean width} * \text{depth}}$$

(iv) Use Table 5.1 in Volume II to obtain an initial estimate of the distance from the intake that the extractor should be placed.

5.4 Effects of bends and canal structures

Adaption lengths shown in the table should be increased if there are structures in the canal that generate turbulence. Computational models can be used to predict the effect of upstream bends or structures on extractor performance. However, these effects are site specific and it is difficult to formulate general guidelines.

Nevertheless some guidance is still necessary. Firstly, for structures like syphons and cross-regulators that generate high levels of turbulence, and mix sediment in the flow, we suggest the following: if this type of structure is located closer to the intake than the predicted adaption length, then the adaption length should be measured downstream from the turbulence generating structure.

Secondly, for canal bends, we have found from numerical model simulations that bends concentrate sediment towards the inner bank for a considerable distance downstream, so lateral adaption is slow. However, we found that the vertical adaption was much more rapid. The table below gives distances from the outlets of canal bends to the closest point where an extractor would achieve a trapping efficiency as high as its value after full adaption. The distances, termed "adaption lengths for bends", are presented as numbers of flow depths, and were obtained from numerical model simulations. The table also gives the minimum trapping efficiency that would be obtained if the extractor was located near the bend outlet. The conditions assumed are R=15%, TE_{max} = 50% and friction factor $\bar{u}/u_*$ = 20, TE_{max} is the trapping efficiency which would be achieved after full adaption. These values represent a "worst set" of conditions, predicted adaption lengths can be as low as half those tabulated.

Adaption lengths for bends (minimum trapping efficiency round bend is also given in brackets, it applies to case where $TE_{max} = 50\%$).

Angle of bend	**Ratio R_{curve}/b_m**	**Adaption length/depth (minimum TE,%)**		
		$b_m/h = 5$	**$b_m/h = 10$**	**$b_m/h = 20$**
45%	3	75 (33)	56 (42)	50 (46)
	10	60 (34)	46 (45)	33 (49)
	30	55 (40)	33 (48)	– (50)
90%	3	80 (25)	51 (34)	41 (44)
	10	65 (26)	39 (42)	30 (49)
	30	53 (37)	38 (47)	– (50)

R_{curve}	is a radius of curvature of canal bend
b_m	is mean width of a canal section
h	is canal depth

If there is a canal bend between the intake and the proposed extractor location, then the adaption length is:

that computed for a straight channel, plus

the length of the bend, plus

the product of depth and the value given by the table above.

For shallow bends which have only a small effect on trapping efficiency (minimum TE > about 48% in the table above) the predicted adaption length need not be adjusted, as long as the extractor is not to be sited on the bend or immediately downstream.

5.5 Other factors affecting siting

In practice there are other factors which will influence the location of an extractor (see Figure 5.2). Sediment is returned to the parent river via an escape channel. The location of a natural watercourse that can be used as an escape channel, or the need to minimise the length of the escape channel so that its slope, and hence its sediment transporting capacity, can be maximized will often be more important than satisfying the adaption length criteria.

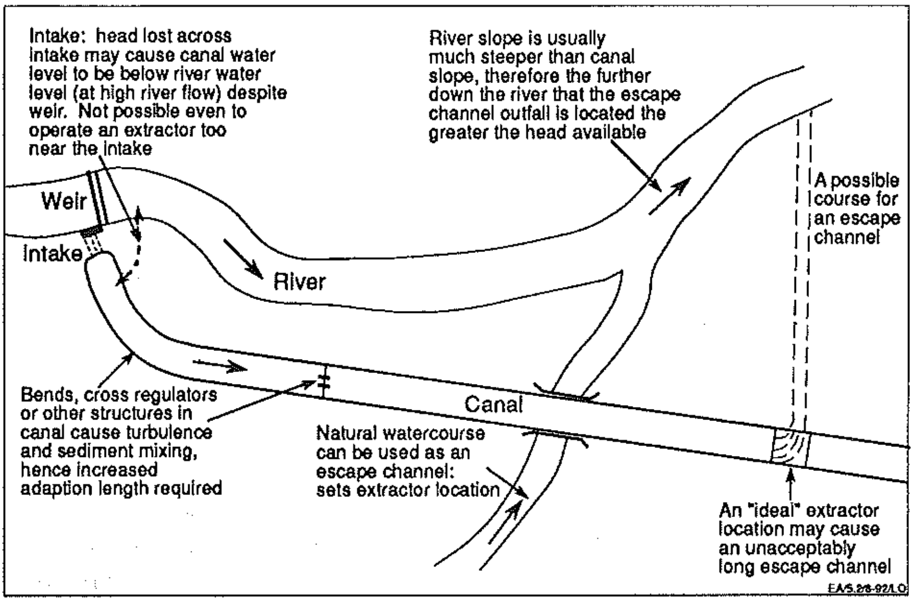


Figure 5.2 Other factors affecting location of an extractor

If the extractor is placed closer to the intake than the predicted adaptation length, then trapping efficiencies will be reduced. As a guide, halving the predicted adaption lengths will reduce the predicted trapping efficiency by about 10% when the predicted trapping efficiency is 50%. On the other hand, increasing the distances will raise water levels at the intake by approximately the extra distance multiplied by the increase in canal slope due to the excess sediment load upstream of the extractor.

5.6 Canal water level at intake

The procedure for estimating canal water level at the intake consists firstly in deriving a canal slope upstream of the extractor. If the canal exists then measurements can be used, otherwise:

DACSE

Using DACSE:
Use the slope which was obtained from the *Canal Depth and Slope* program.

TABLE

Using a hand calculation:
Procedures are described in Appendix 4, Section A4.7.1 to calculate depth upstream of the extractor, they should already have been carried out. If the simple technique for predicting depth was adopted, then step(v) determines the canal water surface slope.

If the full calculation using alluvial friction and sediment transport calculations was undertaken, then the slope was determined by the friction calculation.

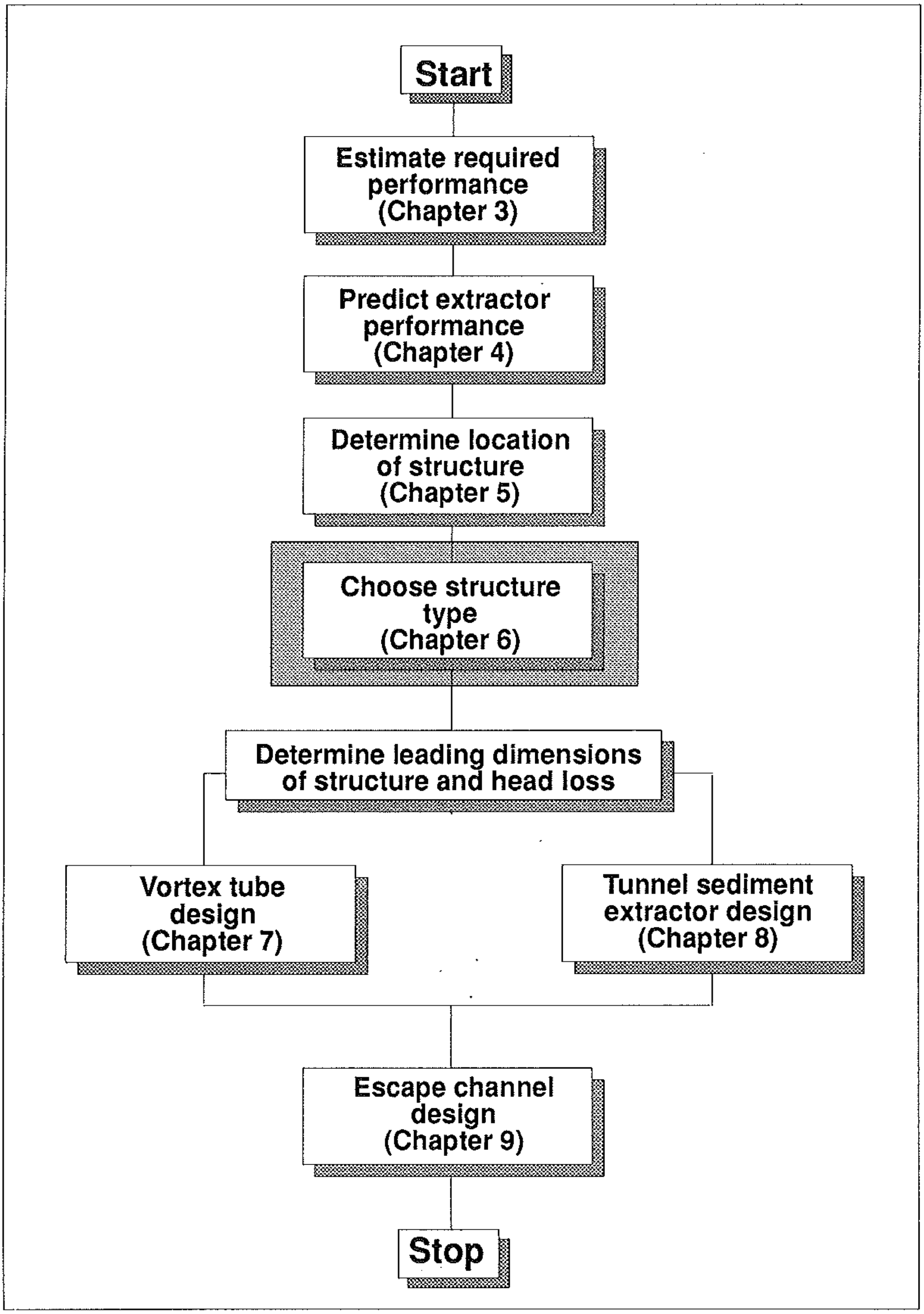
Subtract from the measured or predicted slope, the canal's original design slope. Then multiply by the distance between the intake and the proposed extractor location. The expected water level at the intake is then the design water level plus this value.

5.7 Deposition of coarser sediment near intake

If coarse sediment (gravels and cobbles) enters a canal then it is likely that it will settle near the intake. The canal slope will steepen near the intake and so water levels will rise higher than predicted in Section 5.6. Discharges through the intake may be seriously reduced.

To overcome deposition of coarse sediment in the reach between the intake and the extractor, some mechanical desilting of the canal headreach could be allowed for, or improvements to sediment exclusion at the intake may be possible.

If the canal exists then the problem will already be apparent. For new schemes it is difficult to predict the volumes of coarse sediment which will enter the canal. It will depend on river characteristics, intake siting and design and the gate operations during floods. An indication of when the problem might occur is given by the procedure for estimating the canal bed material grading. Both the DACSE option *Canal Bed Material Grading* and the method of Appendix 3, Section A3.2 provide warnings when the predicted maximum sediment size entering the canal exceeds the maximum size which can be transported.


Start
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Determine leading dimensions of structure and head loss
Vortex tube design (Chapter 7)
Tunnel sediment extractor design (Chapter 8)
Escape channel design (Chapter 9)
Stop

6 Choice of structure

Methods for designing both vortex tube and tunnel extractors are presented. Although the trapping efficiency model used in the manual predicts similar trapping efficiencies for vortex tube and tunnel extractors, there is evidence that in some locations vortex tubes will have a higher efficiency, (Ahmad and Ali 1962). Other factors to be considered are:

- Cost
- Head loss
- Susceptibility to sediment deposition within extractor
- Ease of access for maintenance
- Susceptibility to blockage by trash

Vortex tube extractors are superior to tunnel extractors when judged by the first three criteria above, but large numbers of tunnel extractors have been constructed, particularly in the Indian sub-continent. Tunnel sediment extractors have mostly been constructed in canals carrying a discharge of over 100m^3/s.

It is recommended that a vortex tube extractor is considered first unless access for maintenance or blockage by trash are overriding considerations. Outline designs can be attempted for both types of extractor, and evaluated against the criteria listed above, together with other factors that may be important locally. (See Figure 6.1.)

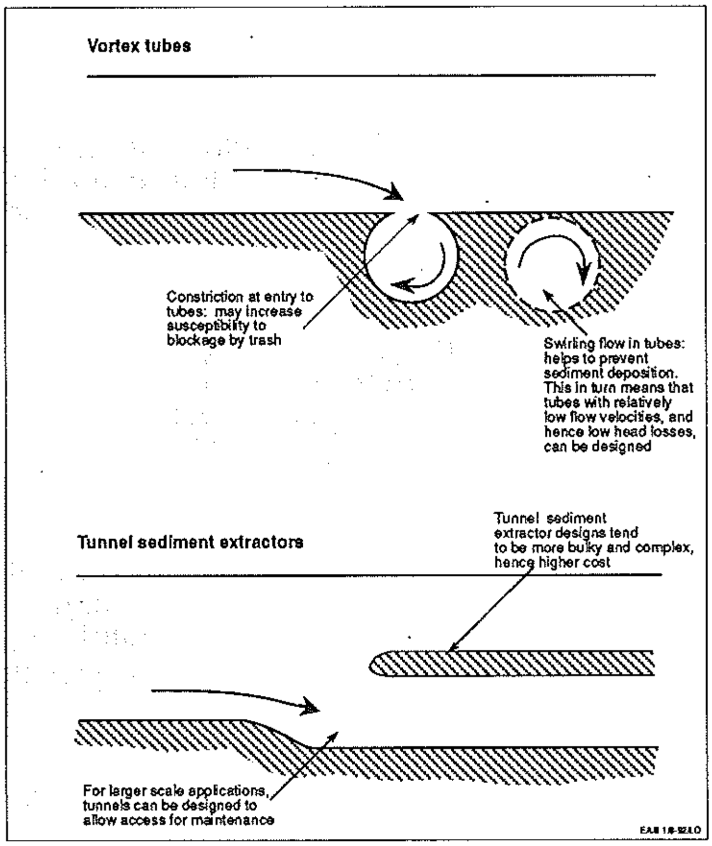
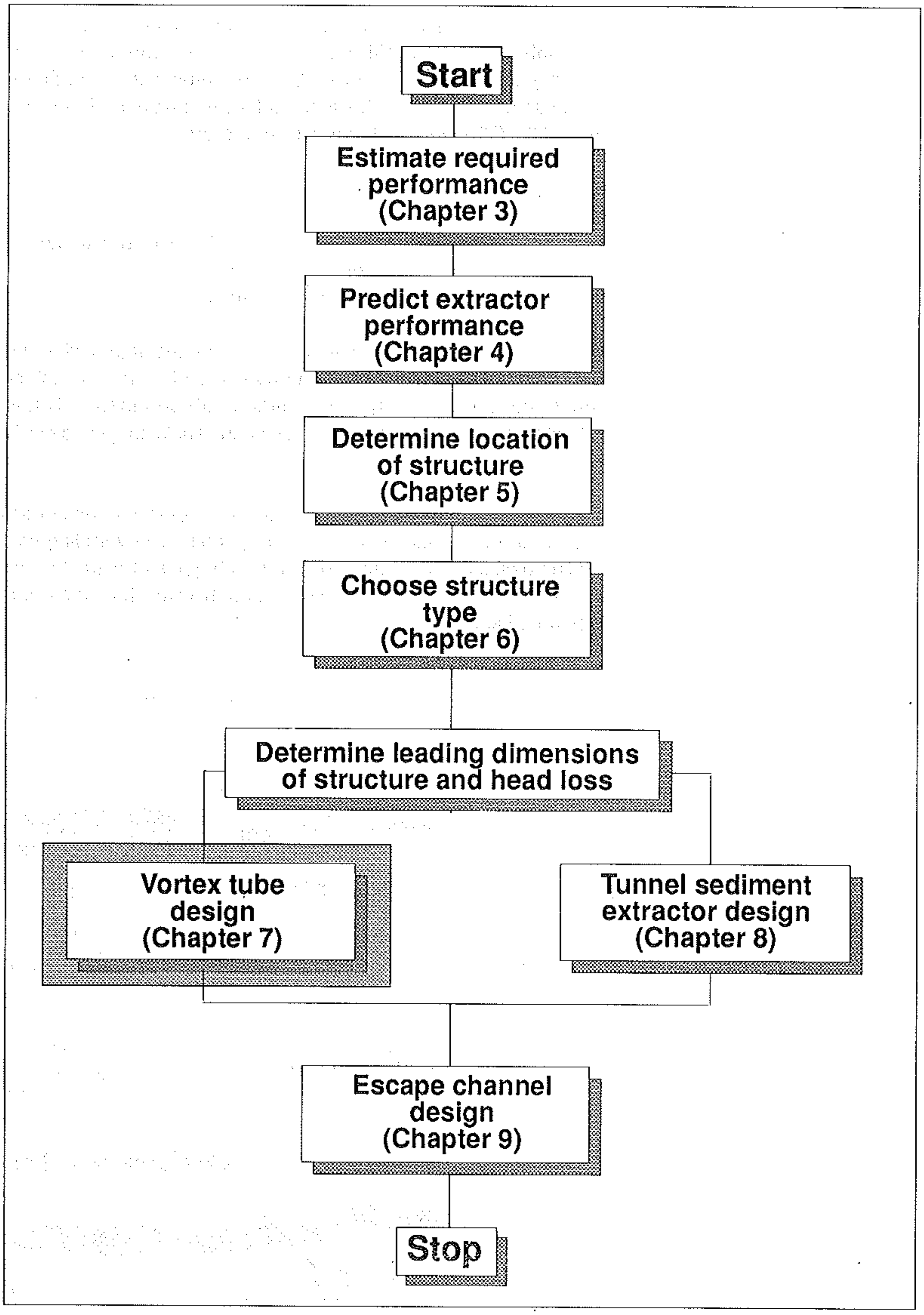


Figure 6.1 Comparison between vortex tubes and tunnel sediment extractors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Stop

7 Vortex tube extractor

7.1 Introduction

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 is diverted through the vortex tube and discharged from the canal to an escape channel. Figure 7.1 shows the principle. 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. Figures 7.2 and 7.3 show plan views of two vortex tube extractors. The first is a simple single tube design, the second, constructed in a larger canal, is a multiple tube design, see also Figure 7.4.

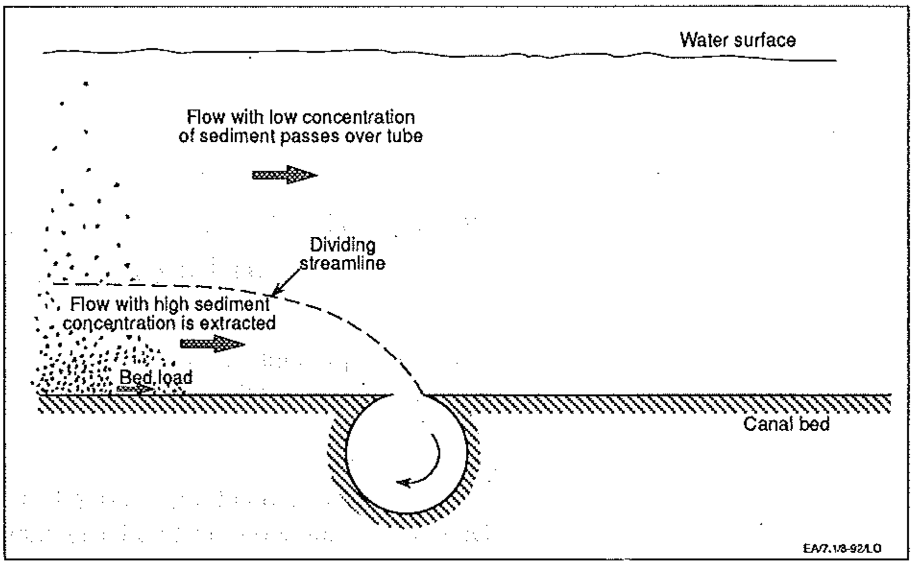


Figure 7.1 **Section of a vortex tube sediment extractor with one tube**

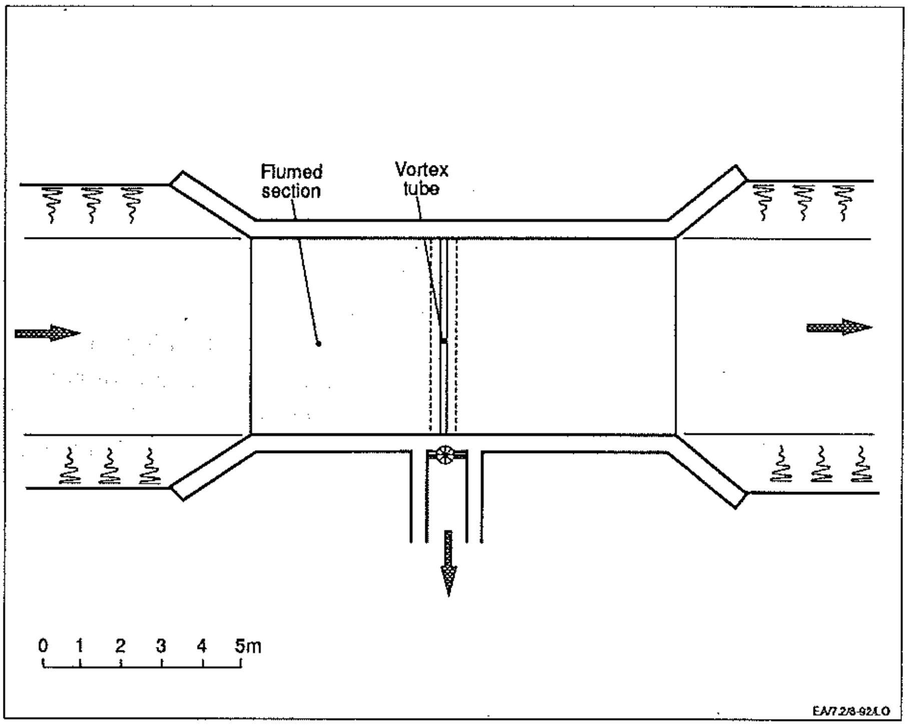


Figure 7.2 Plan of vortex tube on the Warujayeng-Kerlosono Irrigation Scheme, Java

This chapter presents the method for determining the leading dimensions of the vortex tubes and the number of tubes required.

The design procedure is based on the theory presented by Sanmuganathan (1976). Two design criteria are used. Firstly the tangential velocity at the closed end of the tube must be large enough to prevent sediment settling in the tube. Secondly the head loss across the tube must not be excessive. These lead to conflicting requirements because the high velocities required to prevent sediment deposition result in large head losses. In practice this, and the requirement of an even extraction along the tube to maximise trapping efficiency, results in a limit in the tube length that can be used. Multiple tube installations such as that shown in Figures 7.3 and 7.4 are often required.

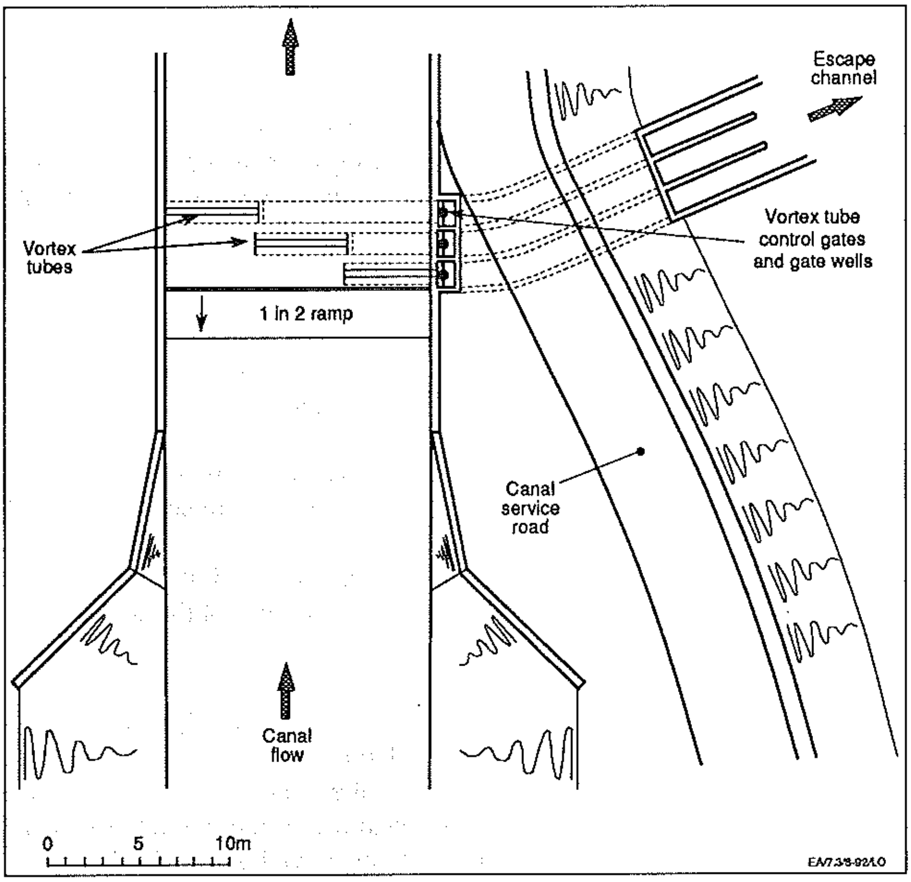


Figure 7.3 **Plan view of vortex tube sediment extractor at RD39, Chatra Canal, Nepal**

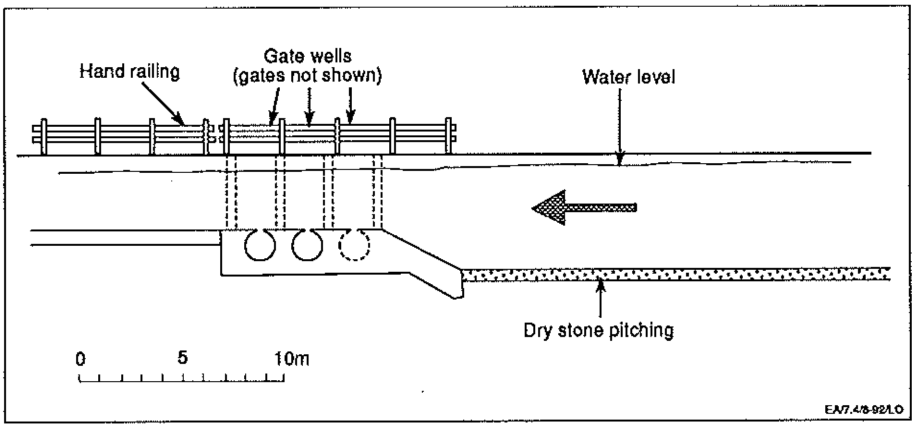


Figure 7.4 **Section along canal centreline at vortex tube sediment extractor, RD 39, Chatra Canal, Nepal**

Vortex tubes have sometimes been designed with tubes at an angle to the flow, not perpendicular as shown in Figures 7.2 and 7.3. However, laboratory studies at HR Wallingford have shown that perpendicular tubes are preferable as the swirl velocity is maximised and the tube length minimised. (Lawrence and Sanmuganathan, 1983.)

The design is carried out with the aid of either DACSE or the tables presented in Volume II.

7.2 Data required

The following data are required in order to carry out a design, data requirements are discussed in more detail in Appendix 4, see also Figure 7.6.

- A cumulative size grading curve for the canal bed material at the extractor location.
- The width and discharge in the canal reach upstream from the extractor.
- A estimate of the maximum allowable head difference between the canal and the upstream end of the escape channel.

DACSE users also need an estimate of the temperature of the canal water and the specific gravity of the bed material sediment.

7.3 Procedure

The principal steps in the design procedure are summarised in the flow chart shown in Figure 7.5. A design is attempted initially for a single tube spanning the canal, if the "head loss" or "no deposition" criteria cannot be satisified then designs with two or more tubes are attempted until one or more acceptable configurations have been derived.

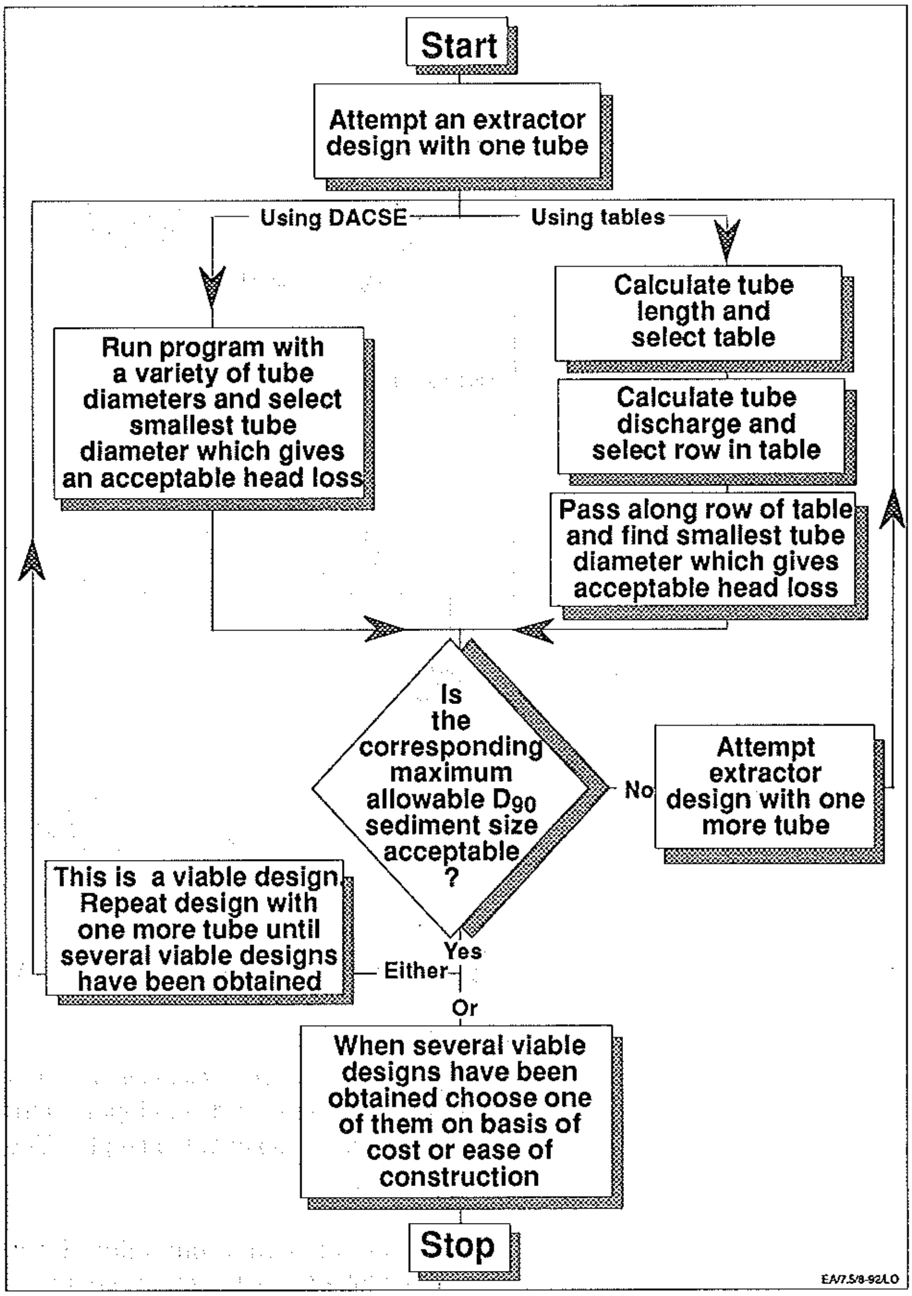


Figure 7.5 Flow chart for the design of a vortex tube sediment extractor

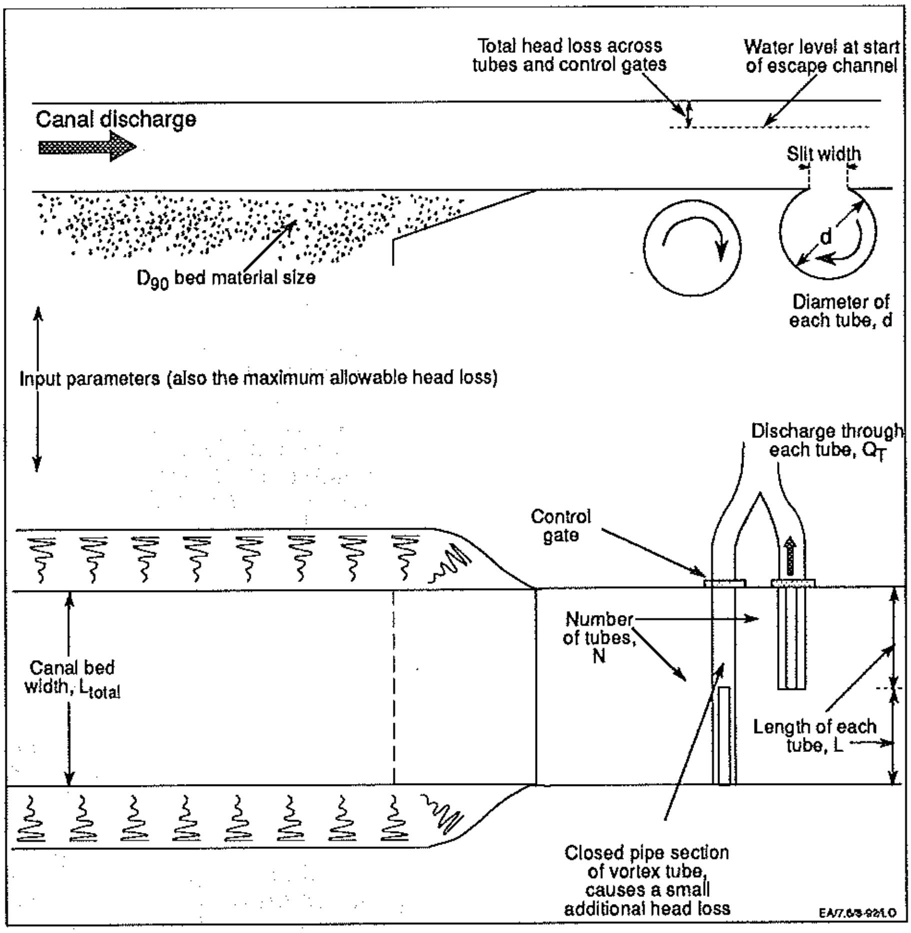


Figure 7.6 Parameters in vortex tube design

DACSE

Using DASCE:
The option *Vortex Tube Design* is selected from the main menu. Initially set the number of tubes at 1 and input an initial tube diameter, for example a value of about one sixth of the length. The design parameters are illustrated in Figure 7.6.

Repeat the calculation changing the tube diameter until the smallest convenient tube diameter which produces an acceptable head loss is found. If the initial head loss is too high then a larger diameter should be used, while if it is small then a smaller diameter tube could be used.

The head loss given by the program includes friction loss in the closed pipe section in multiple tube designs, and the exit loss at the outfall to the escape channel. It does not include an allowance for the head loss produced by the control gate at the vortex tube outlet which must be calculated separately.

(The exit loss is taken as the velocity head in the tube in DACSE, if the available head is very limited then a more detailed calculation of exit loss may be justified. An example of the methods used is given in Section 8.3.3 (iv). If the more detailed calculation is carried out then the velocity head, $V^2/2g$, should be subtracted from head loss across the tube given by the DACSE program, and then the new estimate of exit loss added.)

The maximum allowable D_{90} sediment size, D_{90max}, is also output by DACSE. If it is less than the D_{90} sediment size in the canal then the tubes may block. In this case a design with one more tube should be tried, until D_{90max} is less than D_{90} of the canal bed sediment, and the head loss is acceptable.

DACSE

More than one viable design can be prepared and the most suitable selected. The final choice of tube length and diameter may be influenced by the availability or ease of construction of the pipes used to form the vortex tubes.

The slit width at the top of the tube is output for each design case.

If the ratio of tube length to tube diameter, L/d, is more than 6 the variation in water extraction along the length of the tube will result in a small reduction in sediment trapping efficiency. When L/d is 10, the largest value recommended, trapping efficiency will be reduced by about 4%. DACSE prints a warning when L/d is larger than 6 and gives an estimate of the reduction in trapping efficiency that can be expected.

Using the tables:
The procedure is

(i) The total length of the vortex tubes must be set equal to the bed width of the channel upstream of the extractor. Let this total length be L_{total}. Initially a design with a single tube should be attempted. If this proves impossible then attempt a design with two, and if this still is impossible, three or more tubes. For each number of tubes, N, the length of an individual tube, L, is:

$$L = L_{total}/N$$

(ii) The discharge through each tube, Q_T, is

$$Q_T = Q_c{}^{*}\ R/N,\ m^3/s$$

where:

TABLE

Q_c = the canal discharge in m^3/s

R = the extraction ratio of the extractor, as defined in Section 2.1 of the manual, expressed as a number not a percentage. (ie 0.08 not 8%)

(iii) Design tables are included in Volume II. Each table is for one tube length, select the table for the tube length nearest to L. If L is greater than 30m, the maximum tube length tabulated, then the extractor must be designed with more tubes.

Look down the left hand column of the table ("Discharge through tube") until the tube discharge nearest Q_T is found. Now look along the row of predicted head losses (H_{loss}) until a low enough head loss is found. The predicted head loss should be less than or equal to the maximum allowable head loss of the extractor. The predicted head loss includes the exit loss at the outfall to the escape channel, but does not include an allowance for the head loss produced by the control gate at the vortex tube outlet. This should be calculated separately.

(In the tables, the exit loss is taken as the velocity head in the tube. If the available head is very limited then a more detailed calculation of exit loss may be justified. An example of the methods used is given in Section 8.3.3 sub-section (iv). If the more detailed calculation is carried out then the velocity head, $V^2/2g$, should be subtracted from head loss given in the tables, and then the new estimate of exit loss added.)

For designs with more than one tube there is an additional head loss: that produced by the closed pipe from the slotted section of vortex tube to its outfall. This can be significant, and is estimated as follows:

$$\text{Head loss} = \frac{(L_{total} - L)\, Q_T^2}{346\, d^5}$$

where:

L_{total}, L and Q_T are defined in (i) above, and

d = diameter of tube (m), is given at the head of the column in the design table.

The equation gives head loss in meters for the longest tube, it is based on Miller (1971), with a high roughness value assumed.

(iv) When a suitable head loss has been found, then the tube diameter at the head of that column of the table should be recorded. The maximum allowable D_{90} sediment size (D_{90max}) should also be noted, it is the number immediately below the head loss number. If the D_{90} sediment size in the canal is larger than D_{90max}, then sediment may settle in the tube. A design with one more tube should be attempted, returning to step (i).

The tube length, L, may not be equal to one of the tabulated tube lengths, and the tube discharge may not be equal to one of the tabulated discharges. If necessary, linear interpolation will provide a closer estimate of the tube diameters required to satisfy both the head loss and no deposition criteria.

(v) More than one viable design should be prepared and the most suitable selected. The final choice of tube length and diameter may be influenced by the availability or ease of construction of the pipes used to form the vortex tubes.

(vi) The slit width at the top of the tubes should be set as

0.3 * tube diameter

The slit should be set flush with the cill level of the extractor as shown in Figure 7.1.

TABLE

If the ratio of the tube length to tube diameter, L/d, is more than 6 the variation in water extraction along the length of the tube will result in a small reduction in sediment trapping efficiency. When L/d is 10, the largest recommended value, trapping efficiency will be reduced by about 4%. The reduction when L/d is between 6 and 10 can be found by linear interpolation between these values.

7.4 Flushing discharges

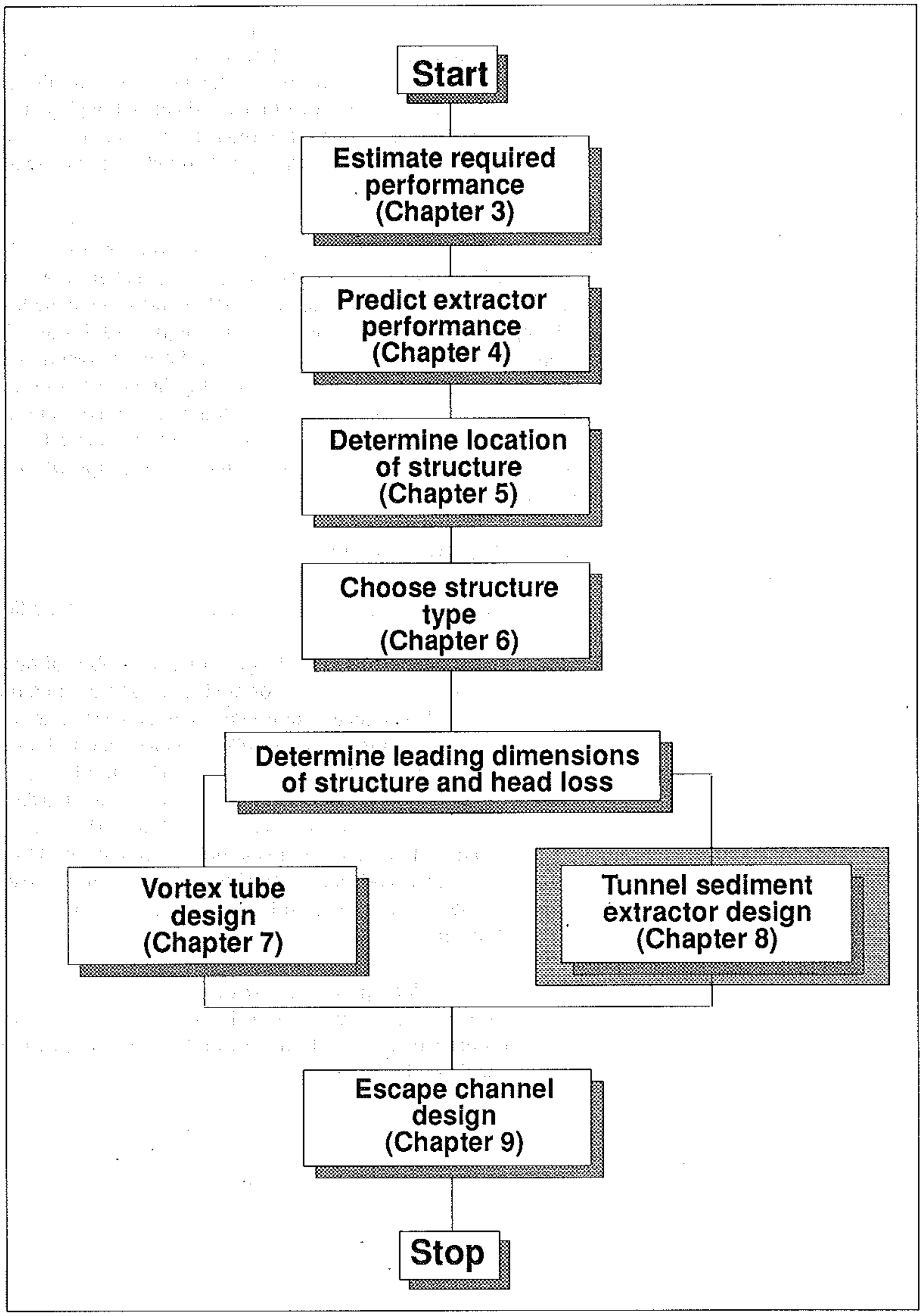
It may be difficult to satisfy the "no deposition" criteria at the operating discharge when a vortex tube sediment extractor is built in a canal with large sediment sizes present in the bed material. If this is the case then tubes can be designed for occasional flushing at a higher discharge. The flushing discharge should be set at about 25% of the canal discharge. The tube diameter should be set using the flushing discharge and the head loss available during flushing. D_{90max} should then be compared with the largest size present in the bed material of the canal. The tube lengths and diameters can then be checked at the lower, "working", discharge which was used in Chapter 4.

7.5 Design options

The following points are relevant to selection of the final design:

(i) The procedure is used to generate a number of design options, which can be assessed for cost and ease of construction. They should also be tested for operation at a smaller extractor discharge, as the extractor discharge will probably need to be reduced when the canal discharge is reduced. The head loss at a reduced extraction will, of course, be acceptable but the maximum allowable D_{90} size will need to be checked. Either DACSE should be run again for the expected minimum extraction, or the column in the design tables relating to the chosen tube length and diameter should be looked up again, and D_{90max} checked for the minimum tube discharge.

(ii) If the designs generated by the design method have large tubes (greater than say 1.5m in diameter) or an unacceptably large number of tubes, then a tunnel sediment extractor could be considered.


Start
Estimate required performance (Chapter 3)
Predict extractor performance (Chapter 4)
Determine location of structure (Chapter 5)
Choose structure type (Chapter 6)
Determine leading dimensions of structure and head loss
Vortex tube design (Chapter 7)
Tunnel sediment extractor design (Chapter 8)
Escape channel design (Chapter 9)
Stop

8 Tunnel sediment extractors

8.1 Introduction

A tunnel sediment extractor consists of a row of tunnels placed at the bed of a canal that divert water and sediment flowing near the bed of the canal. Figure 8.1 shows the principle. Figures 8.2 and 8.3 show plan views of typical extractors, and a front elevation is shown in Figure 8.4.

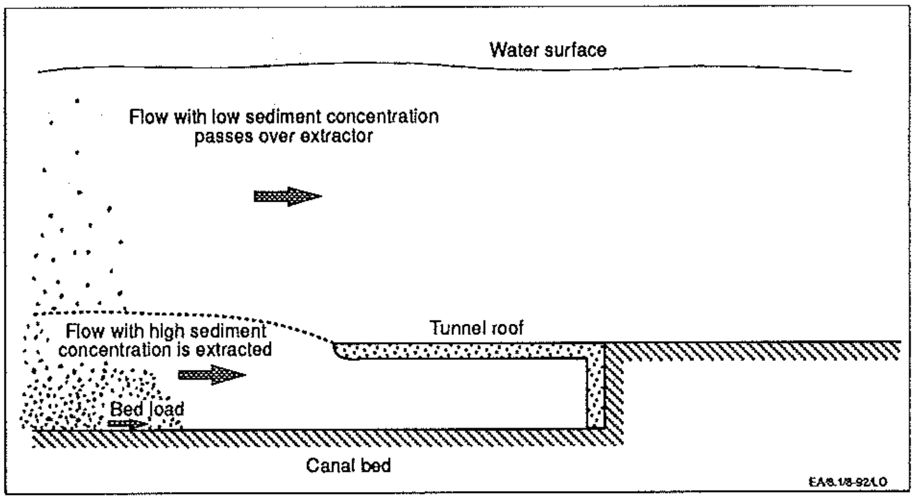


Figure 8.1 Elevation of a tunnel sediment extractor

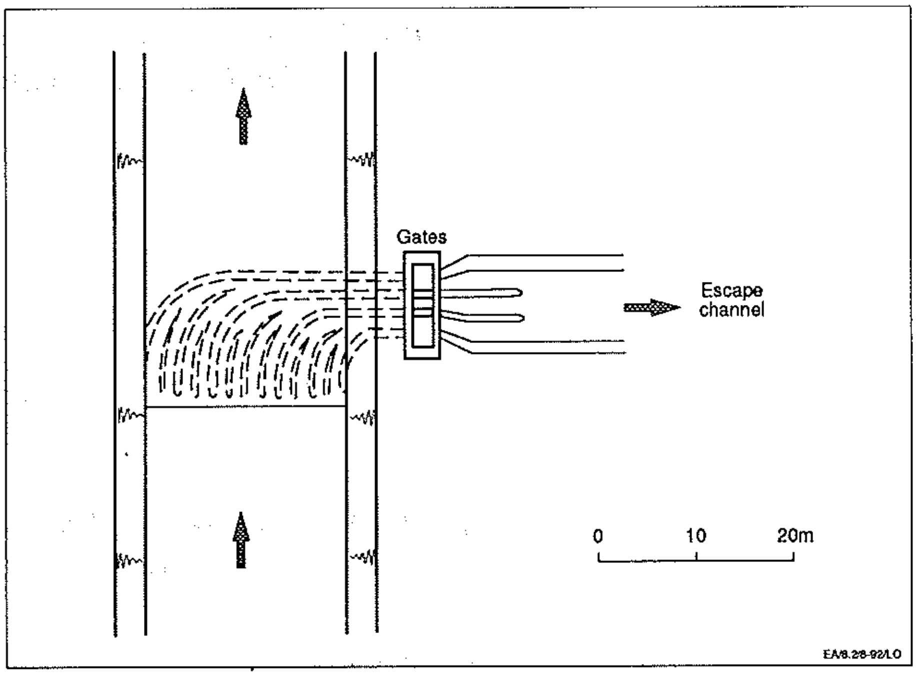


Figure 8.2 Sediment extractor on Salempur feeder, India

An initial design for a tunnel extractor will usually be based on designs that have proved successful at other locations. If the design does not follow the design used in earlier structures, hydraulic model studies have often been recommended to ensure that the hydraulic performance will be satisfactory.

Here we assume that the designer has prepared an outline design, the procedures described in this chapter can then be used to finalise the leading dimensions, estimate the head loss and check that the extractor will not block with sediment.

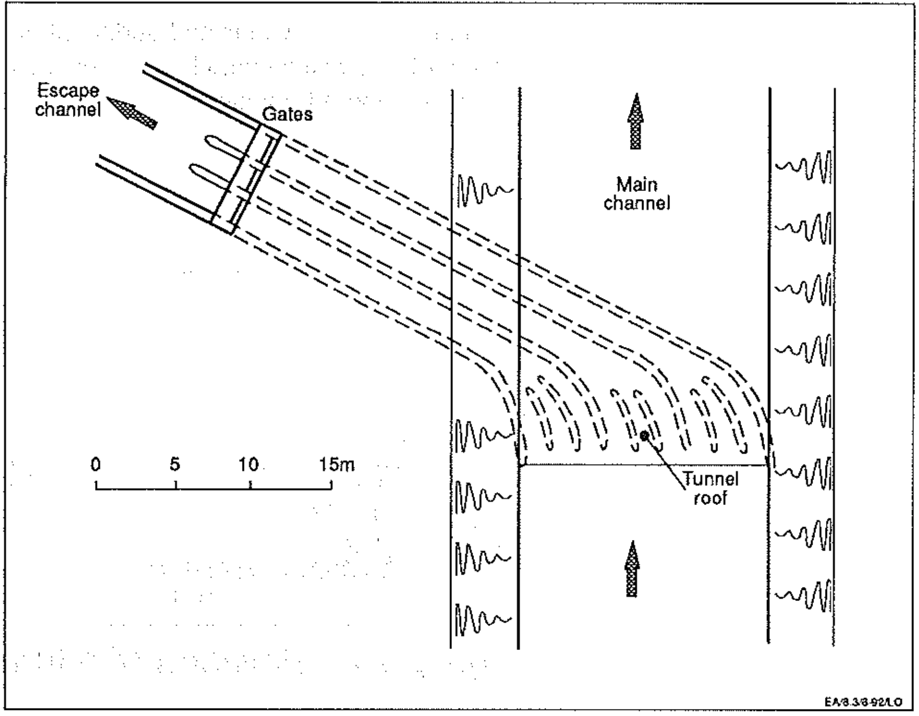


Figure 8.3 **Sediment extractor at RD 10500 on UBDC Hydel Channel, Punjab, India**

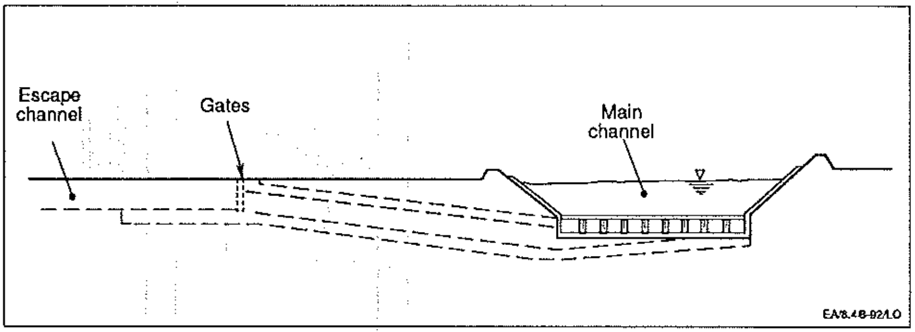


Figure 8.4 **Front view of UBDC Hydel Channel extractor**

The design procedure is based on satisfying two criteria. Firstly that the tunnels should not block with sediment, and secondly that the head loss across the structure should not be excessive. Non-depositing tunnel cross sections are designed using a modification of the Ackers and White (1973) sediment transport equation which was made by Ackers (1986) to allow the equation to apply to conduits. Head losses through the tunnels are predicted using the procedures presented in Miller (1971).

A safety factor of 2.0 is included in the head loss table and equivalent DACSE calculation; the factor is based on head loss measurements at a tunnel extractor in India and accounts for effects such as increased roughness in the tunnels due to wear or bed forms.

The method for determining the dimensions of tunnel extractors has not been tested for a wide range of conditions, and could give unreliable predictions where the bed material contains a wide range of sediment sizes. (The equations presented by Ackers use a single "representative" sediment size). Bed material sediments in canals at likely extractor locations will usually have a relatively narrow size grading, and so this restriction will not apply. However, the method should not be applied to design tunnel excluders in rivers where there is a wide range of sediment sizes present in the bed material.

8.2 Data required

The following data are required in order to carry out a design. Data requirements are discussed in more detail in Appendix 4.

- A cumulative size grading curve for the canal bed material at the extractor location, to determine the D_{50} sediment size.
- The width and discharge in the canal reach upstream from the extractor.
- The sediment concentration in the canal upstream from the extractor, and the sediment trapping efficiency at an extraction ratio of 25% (Obtained using the methods presented in Chapter 4).
- An outline plan of the extractor layout, showing tunnel widths, etc (This is discussed further in the text).

8.3 Procedure

The principal steps in the design procedure are summarised in the flow chart, Figure 8.5.

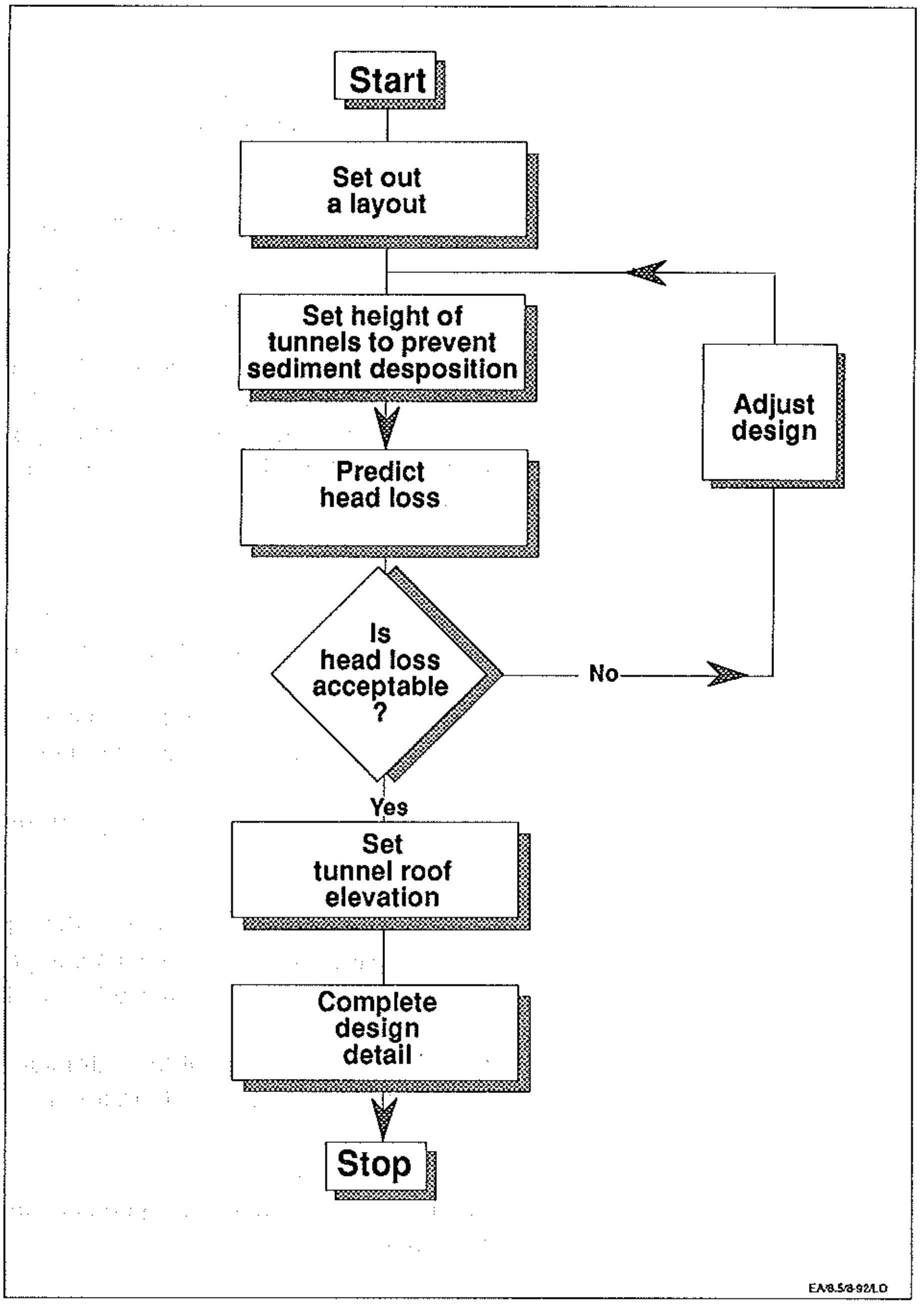


Figure 8.5 Flow chart for the design of a tunnel sediment extractor

8.3.1 Initial layout

An initial plan of the extractor should have been prepared. This should show the tunnel widths, lengths and radii of curvature and the number of tunnels and sub-tunnels.

8.3.2 Tunnel height for no sediment deposition

There will be two or three sections in a typical tunnel layout: an inlet section, a bend section and an outlet section (see Figure 8.6). Some extractors do not have inlet sections, see Figure 8.3 for an example.

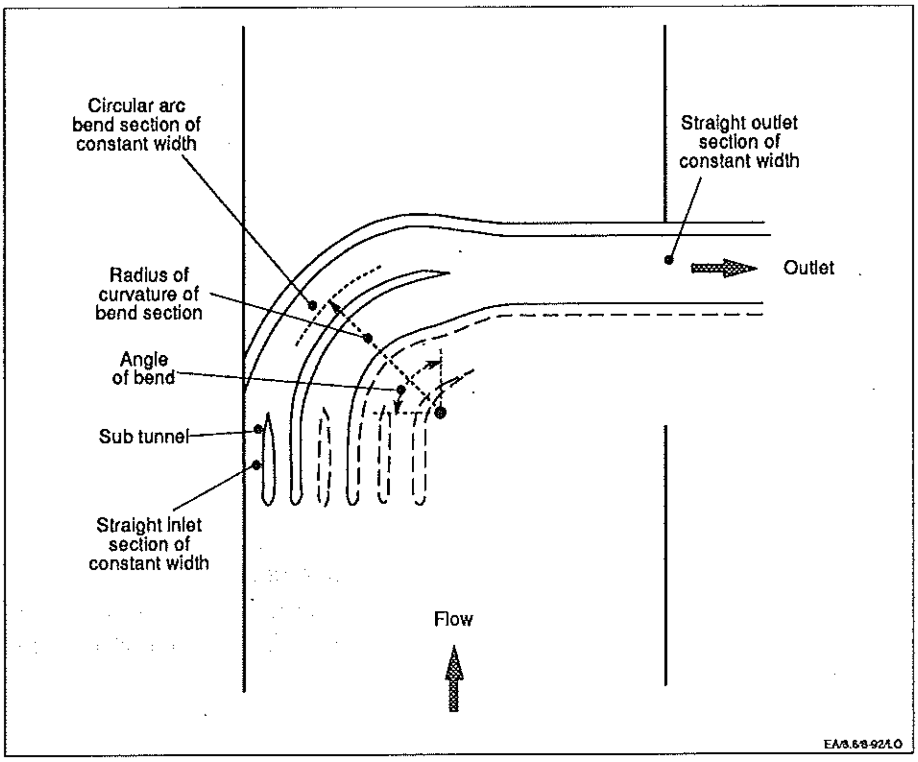


Figure 8.6 Idealised plan of outermost extractor tunnel

For each section the tunnel height can be set such that no sediment deposition will occur at the flushing discharge through the extractor. Tunnel extractors are often operated with water extraction ratios of between 15% and 20%. However they are usually designed so that a larger discharge can be passed through the tunnels. This provides a factor of safety, and ensures that any sediment that settles in the tunnels can be flushed through to the escape channel. A flushing discharge equivalent to a water extraction ratio of 25% is a reasonable choice for initial calculations to set the tunnel heights, although this may need revision later.

The steps are:

(i) Set the flushing discharge as 25% of the main channel discharge.

(ii) Calculate the flow through the individual tunnels of each section:

$$Q_T = \frac{Q_{Flushing}}{N}$$

where:

Q_T = flow through a tunnel, m^3/s

$Q_{Flushing}$ = Flushing discharge, m^3/s

N = Number of tunnels or sub-tunnels at that section.

(iii) Estimate the sediment concentration in the tunnels:

$$X_T = \frac{X_c * TE_{25}}{25}$$

where:

X_T = sediment concentration in the tunnels (ppm)

X_c = estimate of sediment concentration upstream of the extractor (ppm)

TE_{25} = trapping efficiency (in %) of extractor at an extraction ratio of 25%.

(iv) If sediment settles in a tunnel, the height of the sediment deposit will increase until the flow velocity rises sufficiently to prevent further deposition. The tunnel height which remains unblocked, h_f in Figure 8.7, must therefore be predicted:

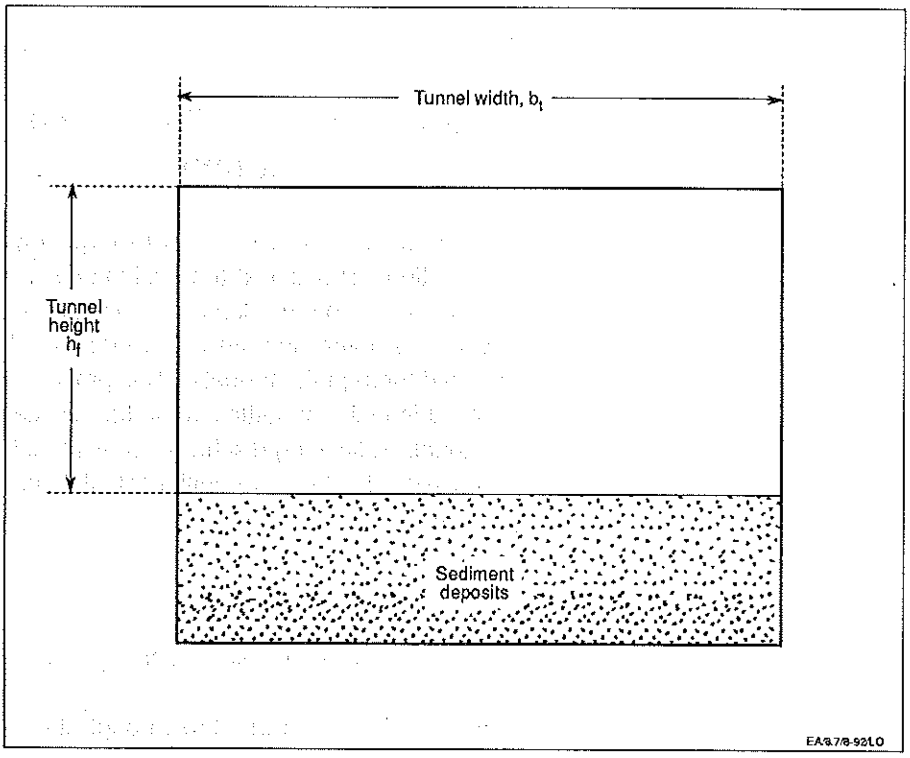


Figure 8.7 Cross-section of a partially blocked tunnel

DACSE

Using DACSE:
Select the *Headloss* option from the *Tunnel Extractor Design* main menu option. (The results of the calculation will be used later to predict headloss, but the program also predicts the tunnel height, h_f, for no deposition). Enter the data requested in the data entry screen, selecting a large initial tunnel height, several times the tunnel width. The output will display the predicted unblocked tunnel height, h_f, and the headloss in mm per m length of tunnel.

TABLE

Using the tables:
Tables 8.1(a) to (h) give the results of a series of computations to determine the height, h_f of flow in a partially blocked tunnel. Use tables 8.1(a) to (h) to find the predicted value of the ratio R_t:

$R_t = h_f/b_t$

where:

b_t = tunnel width

First select the appropriate tables for the sediment concentration, then use linear interpolation to obtain the predicted value of the ratio R_t for each tunnel section. (An example is shown at the front of the tables.)

Using the ratio, the tunnel height is determined from

height = R_t* b_t

(v) For each section of the extractor, the tunnel height should be set either at the value predicted in (iv) or a lower value. The tunnel height could be made greater, but it would then be likely to block partially. The larger cost of construction would produce no benefit.

8.3.3 Head loss

The head loss between the main channel and the outfall to the escape channel has to be less than the head available. The comparison between the available head loss and predicted head loss should be carried out for the longest (outermost) tunnel, see Figure 8.6. The procedure is as follows:

(i) As in Section 8.3.2, set the extractor discharge at 25% of the main channel discharge. The tunnel discharges for the inlet, bend and outlet sections will also be the same as in Section 8.3.2.

(ii) Calculate the head loss per m length of straight tunnel.

DACSE

Using DACSE:
If the tunnel heights output by the program are those chosen for the design, then also use the head losses, H, predicted by the program. If for any section a smaller height is chosen then re-run the program, using the new tunnel height, to determine the head loss.

TABLE

Using the tables:
For each section of the extractor read from Table 8.2 the predicted head loss for the tunnel in mm per m. (Linear interpolation similar to that used with Table 8.1 will be required).

(iii) Calculate the total head loss, in m, due to friction in the tunnels. For each section:

head loss = L * H/1000 meters

where:

L = length of tunnel section (m)
H = predicted head loss from Table 8.2 (in mm per m)

For the bend, this head loss should be multiplied by a factor to account for bend losses, the factor depends on the angle of the bend and the radius of curvature of the bend, which are shown in Figure 8.6. Figure 8.8 should be used to obtain the multiplying factor.

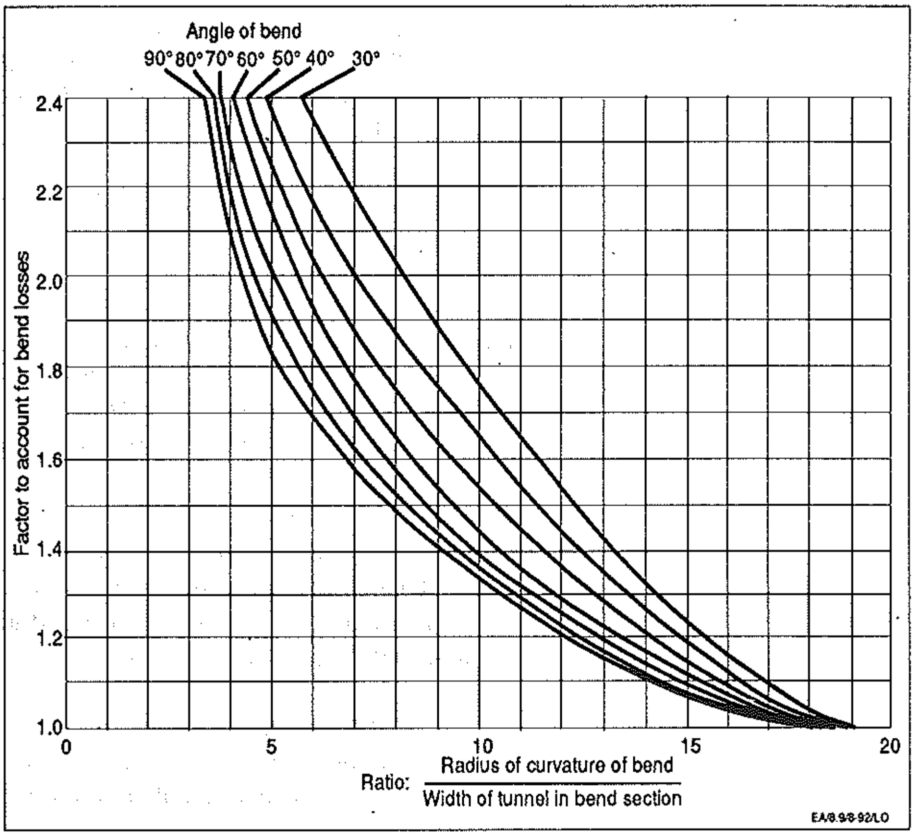


Figure 8.8 Multiplying factor for bend head loss

The individual losses for each section should be summed.

(iv) Calculate the exit loss.

A first, conservative, estimate for the exit loss can be obtained by equating the exit loss to its maximum value: the velocity head at the tunnel exit. Referring to Figure 8.8:

$$\text{Exit loss} = \left(\frac{Q_{ex}}{b_e\, h_e}\right)^2 / 2g$$

where:

g = $9.81 m^2/s$

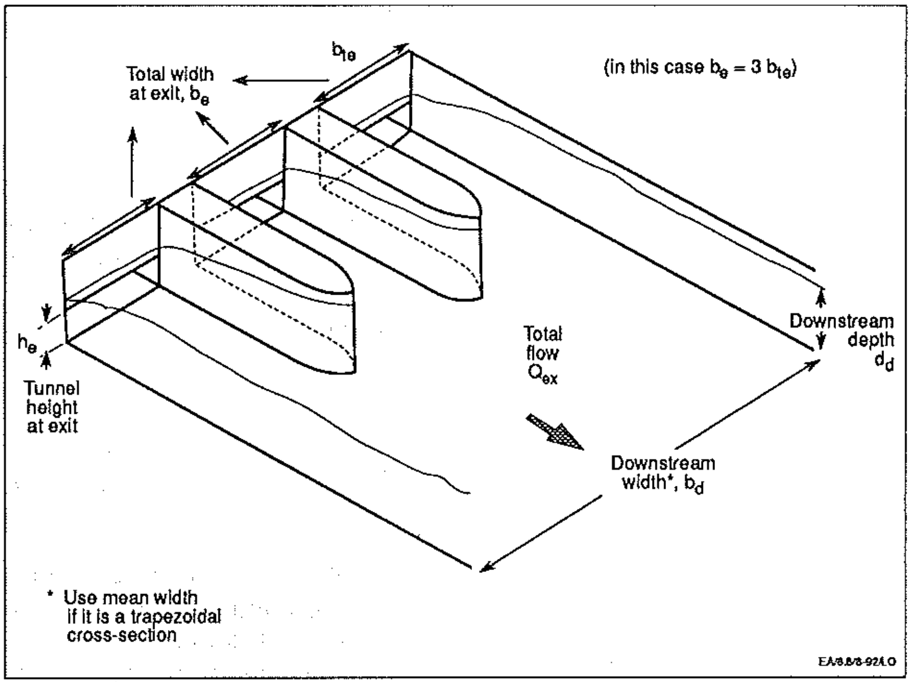


Figure 8.9 Definition of variables to calculate exit loss

If the available head is very limited then a more detailed calculation may be justified. As this requires a knowledge of conditions in the escape channel, an initial escape channel design will have to completed, using the procedure set out in Chapter 9, before the exit loss calculation can be carried out.

The procedure below is valid when flow at the extractor outlet is drowned, and flow in the escape channel is subcritical.

DACSE

Using DACSE:
From the *Tunnel Extractor Design* option select *Exit Loss.* Refer to Figure 8.9 for the definition of the input variable requested, the depth d_d and width d_d will need to be obtained from the escape channel design, Chapter 9. The exit loss is predicted in m.

TABLE

Using hand calculation:
Referring to the definition of variables in Figure 8.9 (the depth d_d and width b_d will be obtained from the escape channel design, Chapter 9).

$$\bar{u}_e = \frac{Q_{ex}}{b_e\, h_e}$$

$$\bar{u}_i = \frac{Q_{ex}}{b_e\, d_d}$$

TABLE

(Note:

$$\text{If } \frac{\bar{u}_e^2 h_e}{g} + \frac{h_e^2}{2} \geq \frac{\bar{u}_i^2 d_d}{g} + \frac{d_d^2}{2}$$

then the outlet is not drowned and the calculation procedure is not valid. Refer to a standard hydraulics textbook.)

Exit loss =

$$\frac{\bar{u}_i^2}{2g} - d_d\left[1 - \left(1 + \frac{2\bar{u}_i^2}{g\, d_d}\left(1 - \frac{d_d}{h_e}\right)\right)^{\frac{1}{2}}\right] + \frac{\bar{u}_i^2}{2g}\left[\frac{2\bar{u}_i^2\, b_e^3\, (b_d - b_e)}{g\, d_d\, b_d^4} - \frac{b_e}{b_d}\right]$$

(v) No allowance is necessary for the head losses across the gates used to control the tunnel discharges, because the headloss calculation is for the flushing dicharge with the gates fully open. If the sum of the friction loss, in (iii), and exit loss (iv) is greater than the head loss available, then the design of the extractor should be revised. The following adjustments to the design could be made:

- Greater tunnel heights (if this did not cause sediment deposition)
- Narrower divide walls between tunnels, making the tunnels wider
- Fewer and hence wider tunnels
- Larger tunnels in the outlet section and at exit

If the calculations in (ii) to (iv) show that the head loss is still unacceptable, then a tunnel sediment extractor is not feasible. A vortex tube sediment extractor could be considered, as this could probably be designed to have a lower head loss.

8.3.4 Elevation of tunnel roof

It is conventional to set the tunnel roof at the same elevation as the dividing streamline, see Figure 8.10.

The height of the dividing streamline (Fig 8.1), can be calculated using DACSE or by using Tables 8.3(a) to 8.3(m).

DACSE

Using DACSE:
The third option under tunnel extractor design, *Height of Dividing Streamline*, should be chosen. Data for the canal just upstream of the extractor should be entered in the same way as for the trapping efficiency calculation. The extraction ratio should be the operating extraction ratio, as set in Chapter 4, not the 25% flushing extraction ratio.

The height of the dividing streamline is output by the program in meters.

TABLE

Using the tables:
The height can be read from Tables 8.3(a) to 8.3(m) using values for:-

- discharge per m width of canal upstream of the extractor (m^2/s)
- Froude number, Fr, of the flow upstream of the extractor

$$Fr = \frac{\text{mean velocity}}{\sqrt{\text{depth} * g}}$$

- Extraction ratio, R: The operating extraction ratio, as determined in Chapter 4 should be used for this calculation, not the 25% flushing extraction ratio.

The elevation of the tunnel roof can be set lower than the elevation of the dividing streamline, but it should not be set higher than the elevation of the dividing streamline. It may be necessary to set the base of the tunnels below the canal bed elevation, as shown in Figure 8.10.

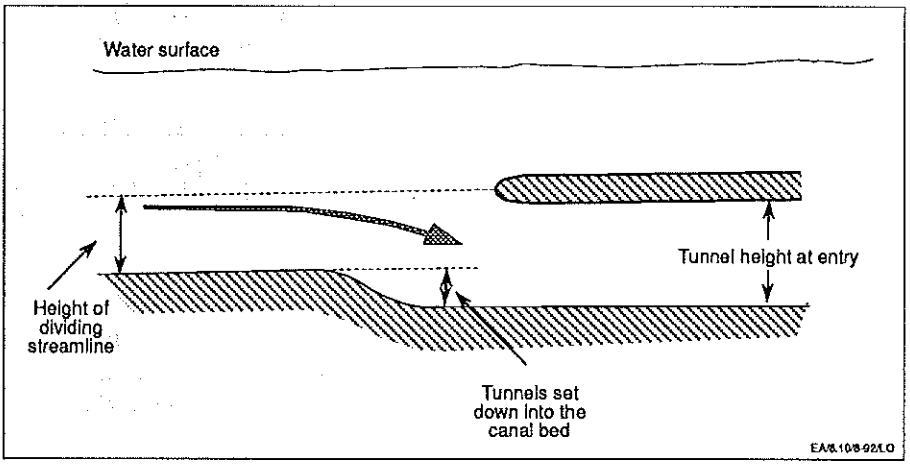


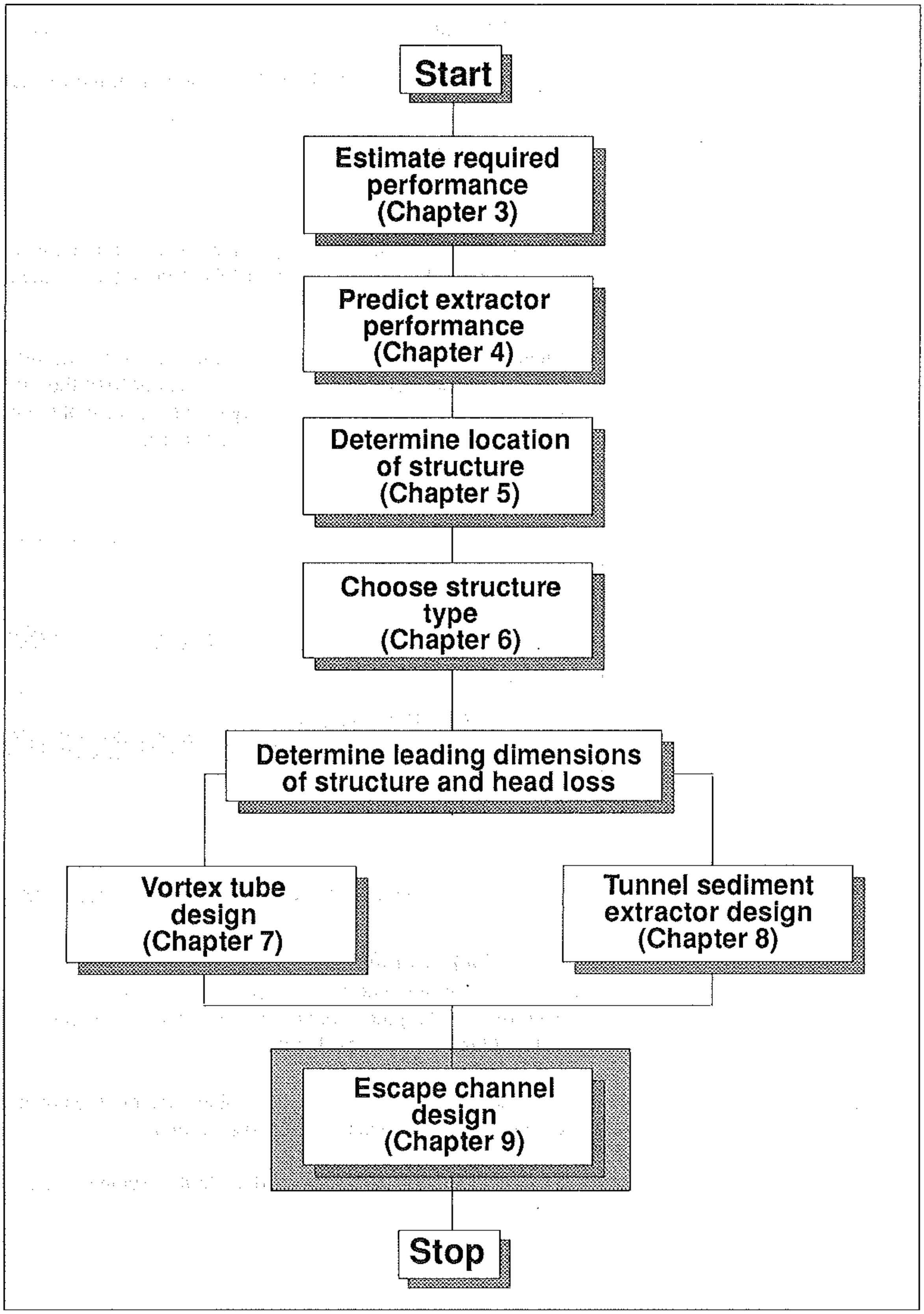
Figure 8.10 Tunnels set down into the canal bed

8.3.5 Design details

The extractor tunnels should each pass an equal discharge, this is often achieved by adjusting the widths of the tunnels so the shorter tunnels have higher head losses per meter length.

The head loss prediction methods presented earlier can be used to adjust the tunnel dimensions to equalize tunnel discharges.

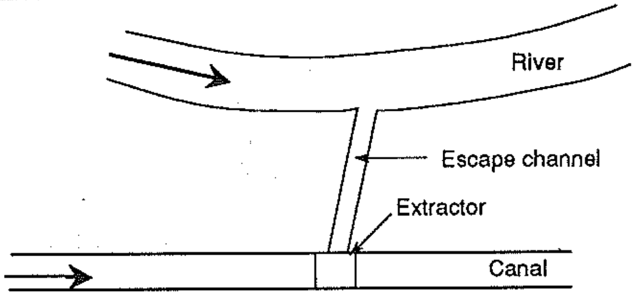
Finally, design streamlined leading edges to the divide walls and tunnel roof.


Start
Estimate required performance (Chapter 3)
Predict extractor performance (Chapter 4)
Determine location of structure (Chapter 5)
Choose structure type (Chapter 6)
Determine leading dimensions of structure and head loss
Vortex tube design (Chapter 7)
Tunnel sediment extractor design (Chapter 8)
Escape channel design (Chapter 9)
Stop

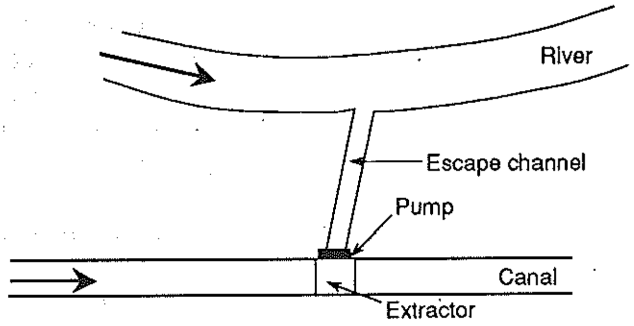
9 *Escape channel design*

9.1 Introduction

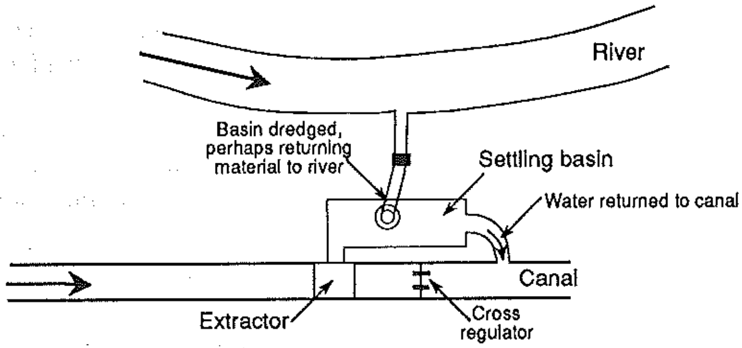
The simplest method of disposing of extracted sediment is to return it to the parent river, via a short escape channel, Figure 9.1. There must be a head difference between the canal and the river for this option to be viable and thus gravity disposal can usually only be used where the river can transport the sediment returned by the extractor when the river discharge is reduced by the supply to the canal. This is not covered in the manual.



(a) Gravity disposal to river (conventional method)



(b) Disposal to river with aid of a pump



(c) Extractor discharges to a small settling basin

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Figure 9.1 Alternatives for sediment disposal

If gravity disposal is impossible, other options can be considered. Sediment could be diverted to a small settling basin which is emptied periodically, perhaps with the extracted water being returned to the main canal. If power

(Water levels and not energy levels are used, as the proportion of the velocity head that is recovered at the escape channel outfall will depend on local conditions. In some cases this will provide a small additional factor of safety.)

The calculation is summarised in Figure 9.2, the steps required are as follows:

(i) Determine the maximum allowable water level at the upstream end of the escape channel. It is the water level in the canal at the design discharge minus the predicted head loss across the extractor, (include the head loss across the extractor control gates).

(ii) Include a margin of safety at the upstream end of the escape channel, to allow for accretion in the escape channel. The margin of safety will allow for (a) inaccuracy in the sediment transport equation used to calculate escape channel slope, and (b) seasonal affects such as accretion due to short periods of high sediment loads being abstracted from the canal or periods with a low extractor discharge. The margin of safety should be at least 25% of the product of escape channel slope and length. The upstream bed elevation in the escape channel is then set from the new design water level minus predicted flow depth.

(iii) The bed and water surface elevations at the downstream end of the escape channel are then determined as those at the upstream end minus the product of escape channel slope and length.

(iv) Check that the water surface elevation at the escape channel outfall is higher than the river water surface. The river water level is derived from the stage discharge curve using the flow with a specified return period. A further margin of safety may be advisable here, if accretion in river bed levels is expected, Figure 9.2.

(v) If the criteria in step (iv) cannot be achieved then consider one of the options listed below:

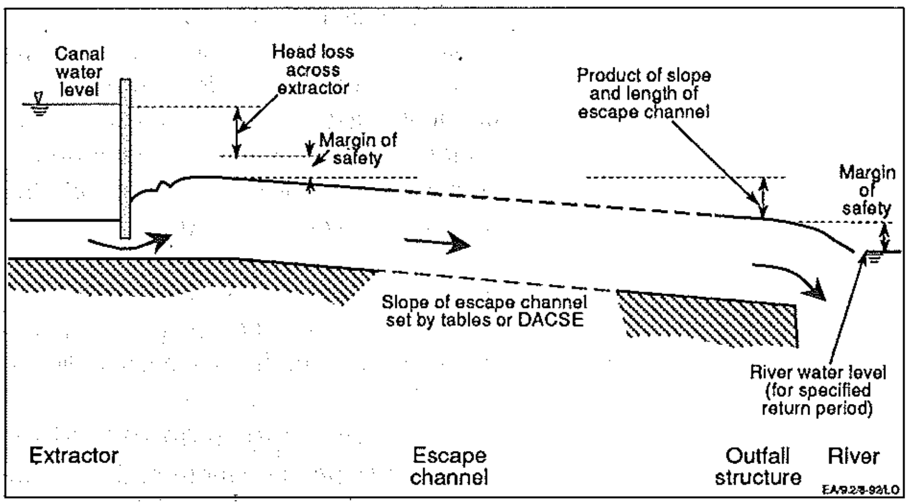


Figure 9.2 Head available to operate escape channel

9.5 Options if available head is insufficient to operate escape channel

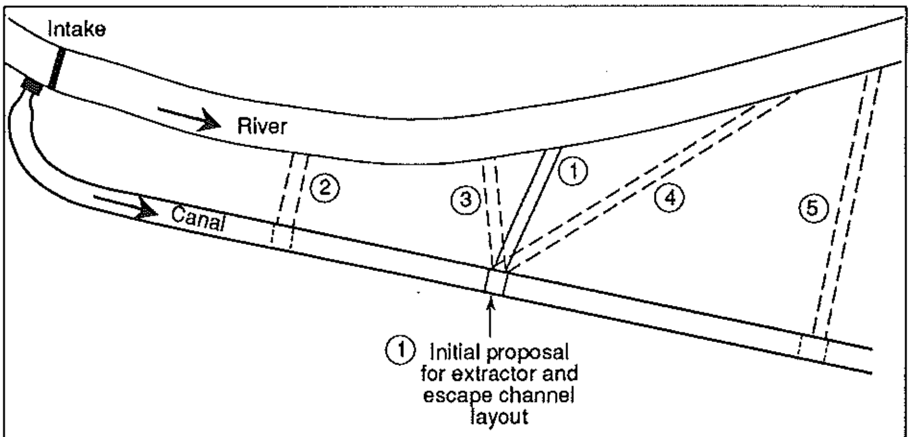
(i) Avoid operating the extractor for the (probably short) periods when river levels are very high, (design for maximum river water level with a shorter return period). The canal may be closed during these periods anyway, for example when high river flows are associated with high rainfall in the irrigated area.

(ii) Re-site the extractor or re-align the escape channel, see Figure 9.3.

(iii) Increase the design water level in the canal at the extractor location.

(iv) Re-design the extractor for a smaller head loss.

(v) Consider using an alternative method of sediment disposal.



Resiting the extractor (options 2 and 5) or re-aligning the escape channel (options 3 and 4) may overcome problems of lack of head to operate the escape channel. Options 2 and 3 may help by shortening the escape channel. Alternatively, options 4 and 5 may help if the river slope is much larger than the canal slope

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Figure 9.3 Some options if insufficient head to operate escape channel

9.6 Options if the head required to operate the escape channel is less than the head available

(i) Include a higher margin of safety at the upstream and downstream ends of the escape channel.

(ii) Design an extractor with a higher head loss, for example vortex tubes with a smaller diameter.

(iii) Increase the slope of the escape channel and prevent scour by lining.

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(A separate reference list for the alluvial friction and sediment transport equations is given in Appendix 2, Section A2.16).

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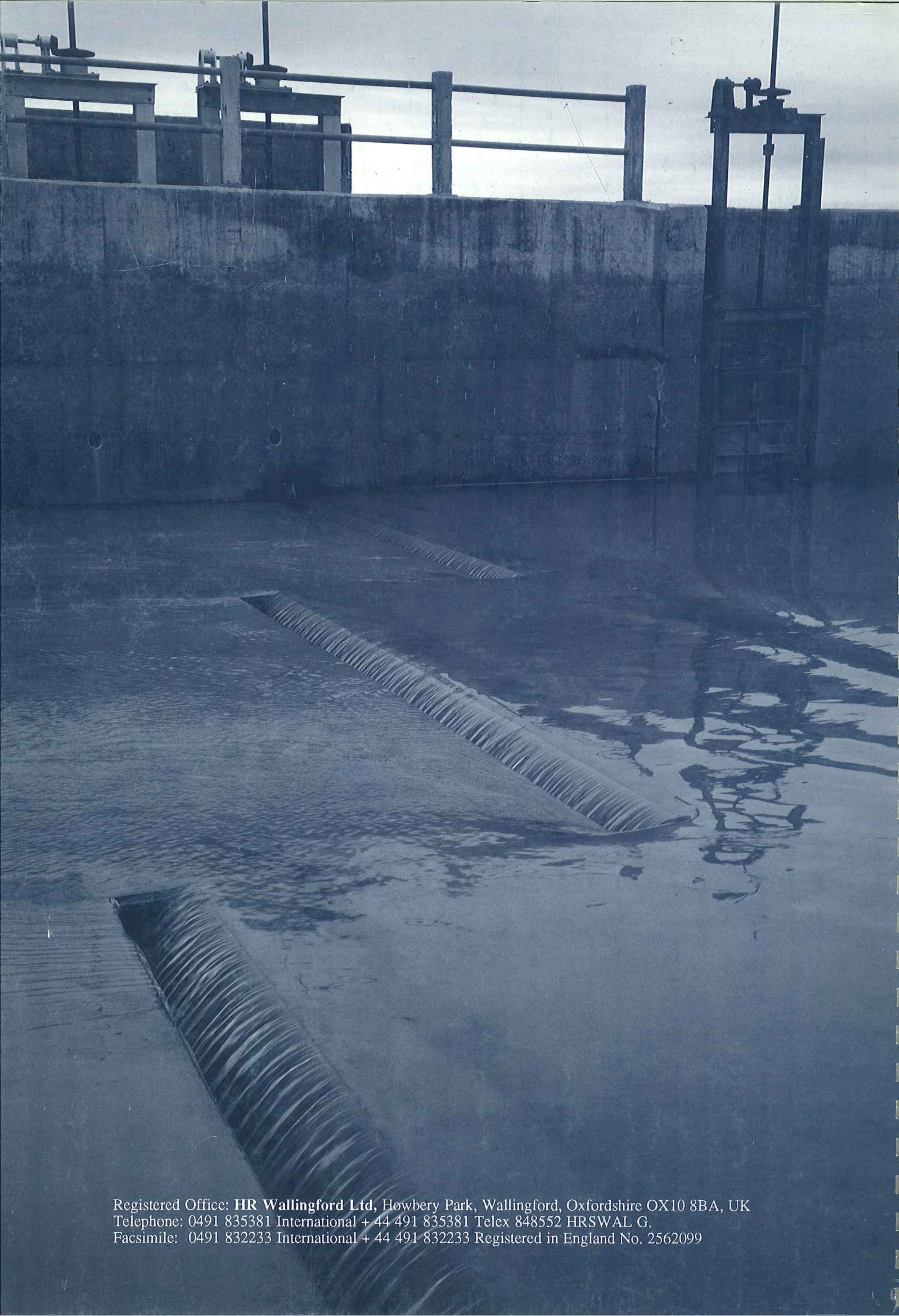

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