Fluvial Design Guide

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Statement of use

The report is provided for consultants and Agency officers preparing engineering designs for fluvial flood defence works. The document directs those undertaking design work to appropriate references to be consulted when considering design of any part of a fluvial defence scheme.

Research Contractor

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EXECUTIVE SUMMARY

This Environment Agency Research and Development document provides access to the information needed to design river works procured by the Agency. It is aimed at those involved in managing design projects as well as those undertaking the design and is therefore intended for use by both Agency and consulting engineers. Its use, however, does not diminish the designer's responsibility to ensure any information utilised is both correct and appropriate for the conditions to which the works are subjected.

The Guide is intended to cover only the process of design, not the full process involved in procuring works, which includes project identification, appraisal and implementation. This process is set out in the Agency's procedures, details of which are given in the list of references appended to Chapter 8. It is important to note that many of the documents produced in satisfying these procedures, particularly the Project Appraisal and the Environmental Assessment documents, will contain much of the information needed during the design process. It is essential, therefore, that these documents and any supporting information should be made available to the designer before design work starts.

It is also important that the designer should be aware of any other issues which may affect the function or operation of the works being designed. These issues include the Agency's general policies on matters such as access, sustainability, environmental sensitivity and enhancement. Local matters, such as public feeling about the work, the risk of vandalism, security requirements, operating procedures and maintenance procedures, particularly frequency of maintenance and plant used, also need to be borne in mind. Some, but not all, of these items will be contained in the Project Appraisal or Environmental Assessment documents.

Following this introduction, the Guide is divided into two parts. The first of these, covering Chapters 1 to 6, describes the basic techniques used to identify and define a problem. The second, covering Chapters 7 to 12, addresses the matters to be considered when designing particular types of river works. It is assumed throughout that a conventional approach to design is followed, in which specific design criteria are established, often using a probabilistic approach (to determine flood levels, for example), following which the works are designed deterministically to satisfy these criteria. It is recognised that other approaches are possible (using a fully probabilistic approach, for example), but they are not covered here. Expert assistance should be obtained if such approaches are proposed.

The philosophy of the Guide is not to give detailed information about each topic, but to identify the important issues and to provide a list of references from which the information can be obtained. Each chapter is in three parts: a brief commentary on the topics covered, a list of references and a table which cross-refers the references to the topics. The references include textbooks, R&D reports produced by the Agency and others, and individual papers.

The reference lists are intended to be comprehensive, but are not necessarily exhaustive. As a result, designers should not feel constrained to use only those references listed; if they wish to use others with which they are already familiar, they are free to do so. Furthermore, they should not be put off if their favoured texts are not included. The original lists were finalised in November 1997 and are being updated annually. The Guide will be reviewed five years after publication in 2003 and feedback from regular users will be sought at that time.

Finally, those using the Guide and the references it contains are reminded that this use does not remove from them their responsibility to check that the designs they produce are effective, safe and appropriate.

KEY WORDS

Channels, channel classification, channel modifications, control structures, fish passes, flood embankments, flood storage, flood walls, flow prediction, fluvial modelling, gates, geomorphology, hydraulics, pumping plant, river restoration, river engineering, sediment movement, sea level rise, tides, tidal surges, telemetry, trash screens.

PART 1 BASIC TECHNIQUES

1. RIVER GEOMORPHOLOGY

1.1 Scope of the chapter

This chapter sets out the role that geomorphology plays in the design of fluvial works for the Environment Agency.

1.2 River geomorphology

River geomorphology is the study of sediment sources, fluxes and storage within a river catchment and of their effect on floodplain and channel forms (morphology) over short, medium and long time-scales. The phrase is also used colloquially to describe the development of a river system under the influence of these natural processes.

Geomorphology is a specialist subject and one that is increasingly required as a component of fluvial design projects. It is most useful during the scoping and feasibility stages to:

- determine whether a project is morphologically sustainable;
- ensure that the resulting morphology and substrate are appropriate for the river type; and
- predict project impacts, with the aim of avoiding the need for additional works after the scheme is built.

1.3 River catchments

River catchments are the fundamental unit of a river's water and sediment transport system. River management therefore requires an understanding of the physical nature of the catchment.

Broadly, a river catchment may be divided into areas relating to the supply (from valley slopes), transport (via the river system) and storage (in the valley floor) of sediments. River channels and their sensitivity to environmental (or other) changes depend on this functional division. The way in which water and sediment are supplied to the river channel can be strongly affected by land cover and land management. Appreciation of this link between the land within a catchment and the river network is an important starting point in the planning of river projects.

1.4 Geomorphology and the Environment Agency

The Environment Agency and its predecessor, the NRA, have invested substantially in geomorphological research and development (R&D). Much of this is available in R&D Reports and R&D Notes, although specific project examples are frequently only available from individual offices. Geomorphology has been used to some extent in all Agency regions, largely in association with river maintenance, capital and restoration works. Although in-house expertise exists, this is comparatively rare, and in most cases expert advice must be sought from outside the Agency. Some in-house expertise remains necessary in order to engage and manage consultants effectively.

The advantages of applying geomorphology include:

- water management – identifying how to work with natural river processes, rather than against them, wherever possible;
- sediment management – establishing cause and effect in river erosion and sedimentation problems;
- ecology and conservation – providing the practical and technical guidance relevant to the Agency's duties to further conservation of natural beauty and physiographic features when exercising its powers, and to consider the effects of works on the river landscape;
- flood defence – producing schemes which are secure, do not require excessive maintenance and avoid unnecessary disruption to natural river processes and habitats;
- fisheries – designing enhancement and restoration schemes which provide the habitat diversity needed to support a range of fish populations;
- recreation – improving river channel, riparian corridor and floodplain aesthetics and attractiveness for a wide range of recreational purposes;

- navigation – ensuring that the Environment Agency's navigation duties and maintenance programmes are performed with due regard to landscape, nature and conservation; and
- water quality – identifying sources of fine sediment causing troublesome turbidity and/or sediment deposition.

1.5 River channel classification

Two important river classifications exist in the UK for the assessment of the conservation value of a river reach:

- the Environment Agency's 'River Habitat Survey'; and
- the Scottish Natural Heritage 'SERCON' (System for Evaluating Rivers for Conservation).

Of the two, the river habitat survey has been established to allow the calculation of a 'Habitat Quality Index' for the national evaluation of river habitat, based on the presence or absence of ecological and geomorphological features for a particular channel 'type'. The SERCON approach uses map-based data for longer 'segments' of the river network, and a set of rules to establish 'conservation values' for a segment. Problems occur with all such classifications, which essentially 'smooth out' the uniqueness of each river reach. Such classifications should therefore only be used to assess the potential management options for a given reach or segment (e.g. restoration or conservation) with the understanding that no works should be undertaken without more detailed study.

1.6 Geomorphology and river engineering

The nature of a river channel has a major impact on river engineering practice. A steep upland gravel-bed river, for example, is very mobile during floods, with large volumes of sediment being moved during such (relatively rare) events causing major changes to the channel morphology. Lowland fine-sediment rivers, on the other hand, are not so violent and so generally adjust progressively rather than intermittently. Engineering practice reflects these differences, both in terms of the strengths of the materials used for river works and in the timing of river maintenance measures.

A recent review of flood defence works and river maintenance practice revealed that in most cases little allowance for sediment movement is made. As a result, the river maintenance undertaken often treats the symptoms of a problem (erosion or deposition) rather than its cause (channel instability). Geomorphological advice can assist in establishing this cause; detailed procedures for assessing bank erosion, sedimentation and general instability are now available and are discussed below.

1.7 Geomorphology and river ecology

The physical habitats found in a river channel are largely determined by the form of the river (planform, cross-section form, long-profile) and its substrate. Habitats are influenced by the rate at which this form and substrate change, as the resulting erosion and deposition dislodge vegetation and benthic organisms and encourage recolonisation. A degree of channel mobility is therefore integral to the preservation of habitat diversity. The type and amount of mobility varies depending on the type of river. River habitat and river corridor surveys can provide a first approximation of river types, but information on channel mobility should be obtained from a qualified geomorphologist. Geomorphology provides functional reasons for the creation and/or preservation of physical habitats and can predict the morphological impacts of their removal and/or creation.

1.8 Geomorphology and river restoration

Geomorphology has a significant role to play in the design of river enhancement, rehabilitation and restoration schemes. The nature of this involvement is fourfold:

- establishment of the degree of physical habitat degradation - what should be present and what is missing (catchment baseline survey);
- establishment of what channel morphology and substrate is appropriate under current water and sediment transport regimes, including the use of historic sources to determine the channel response to extreme events (fluvial audit);

- design of appropriate channel morphology (see Chapter 3); and
- post-project appraisal.

Restoration of physical habitat diversity does not guarantee biological diversity, as poor water quality may impair biological recovery, despite apparent physical naturalness. Physical habitat restoration should not be undertaken without prior assessment of the cause of environmental degradation.

1.9 Emerging practice in the Environment Agency

Standard procedures on geomorphology have now emerged from the Agency R&D programme. A comprehensive guidance document was published in 1997, which includes example briefs for the four procedures mentioned above and outlined further below (reference 10). A standard Agency training course should also be available. Further advice can be obtained from the Agency headquarters at Bristol.

1.9.1 Catchment baseline surveys

A catchment baseline survey is a strategic tool for assessing the geomorphology of river channels throughout a river network. Existence of a catchment baseline survey provides information on the restoration potential and physiographic conservation value of rivers affected by development proposals, and therefore allows rapid and consistent response to such requests for information. Estimated costs are £110 per km for a survey plus report. The survey data takes the form of a series of 1:10 000 scale maps of the river network with reaches classified according to their susceptibility to degradation from human activity, restoration potential and conservation value.

1.9.2 Fluvial auditing

A geomorphological assessment of channel stability and sediment sources, termed a 'fluvial audit', is critical when assessing the cause of an erosion or siltation problem. The technique is used to:

- assess the causes of a perceived management problem prior to proposed capital, maintenance or conservation work; and
- provide the first stage in planning reach rehabilitation or restoration.

Its basis lies in understanding the sediment budget of a reach in the context of the river catchment and thus focuses on the sources, transport and deposition of sediments. A fluvial audit is a stand-alone procedure that uses a combination of field and archive data. Three products are produced:

- a time chart of catchment and river channel changes that may have affected the geomorphology of the system;
- a catchment map which indicates the location of those features important to the development of the river channel; and
- a detailed map of the reach.

These are then used to identify and assess the processes that have led to the current status of the reach in question, and to develop geomorphologically based solutions to the project requirements. Cost is dependent on the level of information required and can range from 0.1 to 10% of the project cost.

1.9.3 Bank erosion assessment

The central tenet for appropriate river bank management is to identify the cause and probable rate of bank erosion. The procedure focuses on identifying erosion processes, the mechanism of failure and the processes responsible for weakening the bank, so leading to failure. Erosion may only be a temporary adjustment, or may be occurring at such a low rate as not to require intervention. Increasingly, it is recognised that eroding banks have important conservation value, providing habitat and landscape quality.

The second principle of appropriate bank management is to gauge whether retreat can be allowed to continue, or should be treated. Carried out in conjunction with a fluvial audit, bank erosion assessments provide solutions that tailor management to the cause of the problem and can be used to provide guidance on appropriate mitigation techniques. The reconnaissance method for addressing river bank management issues comprises a series of guidance sheets for compiling field evidence.

1.9.4 Post-project appraisal

Post-project appraisals (PPA) are an integral part of the environmental assessment process, and without them it is difficult to improve future operations. Specifically PPA can contribute to project regulation, facilitate impact management and aid development of practice.

Geomorphological PPAs can be envisaged as a combination of:

- a 'compliance audit' - checking the degree to which the existing project and its design were compatible; and
- a 'performance audit' - to what extent the aims of the project have been met in terms of channel stability, erosion, deposition;

from which an evaluation of the project can be made on two grounds:

- whether the geomorphological performance of the scheme was met at the design and implementation phase; and
- whether there have been subsequent adjustments that invalidate the project and require remediation.

1.9.5 Collection and archiving of geomorphological data

For each project, it is essential that consideration is given to the collection and archiving of geomorphological data. Information on erosion control, gravel trap maintenance and the subsequent removal of sediments should be considered as part of the maintenance procedures. Similarly, much can be achieved by monitoring key cross sections, or by repeat photography.

1.9.6 Accessing R&D reports

Much of the guidance on applied geomorphology is contained within internal EA reports. Contacts for these include The Centre for Options Appraisal and Risk Assessment, Steel House, London (Dr Andrew Brookes), and The National R&D offices located at EA Head Office, Bristol. Further guidance on the value of River Habitat Survey in geomorphological survey and river channel assessment, may be found by contacting the RHS Lead Region based at Richard Fairclough House, Warrington, Cheshire. At the time of writing, much of the National EA R&D work is under review and a publication summarising all the work to date is due out early 2002.

1.10 References

Topic	References
River morphology	9, 10, 17, 19, 20
River classification	8, 10, 12, 19
River engineering and geomorphology	2, 5, 9, 10, 17, 18, 21
River restoration	3, 4, 10, 11, 13, 14, 15, 16, 20, 19
Scoping and feasibility using geomorphology	1, 3, 6, 7, 10, 21, 22
Designing using geomorphology	4, 15, 16, 19

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2. RIVER FLOW PREDICTION

2.1 Scope of the chapter

This chapter covers the main problems faced in dealing with surface runoff. Issues to be resolved most often concern average and flood flows which are both considered. Problems stem from the need to determine the magnitude and duration of runoff from catchments with respect to time. These can be resolved either by direct analysis of existing records for the study catchment, by transposing data from gauged catchments with similar characteristics, or from the use of generalised relationships derived from the analysis of records from gauged stations.

2.2 Estimation of mean flow

Mean flow is the arithmetic mean of the daily mean flows over a specified period. The estimated mean flow of a study catchment provides a measure of the available resource. By expressing the flow characteristics of gauged catchments as a percentage of their mean flow, the values for a range of different sized catchments in a region can be compared and transposed to ungauged catchments.

For ungauged catchments, an estimate of the mean flow can be obtained using a catchment water balance approach. The average annual runoff depth for a catchment is given by the difference between average annual rainfall (SAAR) and losses. A catchment SAAR value can be obtained either from the map of average annual rainfall for the standard period 1941 to 1970 published by the Meteorological Office (1977) or from the Flood Estimation Handbook CD-ROM (see Section 2.3.2). This CD-ROM holds values of SAAR for the standard periods 1941 to 1970 and for 1961 to 1990. An estimate of catchment losses due to evapotranspiration can be obtained from a variety of sources including:

- the losses recorded in similar gauged catchments, many examples of which are published in the various editions of the *Hydrometric register and statistics* (IoH 1988, 1993 and 1998);
- the MORECS estimates of actual evapo-transpiration for defined 40 × 40km grid squares produced by the Meteorological Office (1981); and
- an estimate of catchment average annual potential evapotranspiration (see Smith 1967 and MAFF 1976) and the adjustment factors recommended by Gustard *et al* (1992).

It should be noted that the above approach deals only with natural losses, whereas over one-half of rivers in the UK now have a non-natural flow regime. When calculating the mean flow of a catchment by the above approach, or when deriving a representative series of annual runoff values for a water resource application, it is essential that any major water supply abstractions and/or effluent returns to or from adjacent catchments are dealt with separately. Guidance on the topic of streamflow naturalisation can be found in 'Flow naturalisation using hydrological models' (British Hydrological Society, 1994).

2.3 Flood estimation

2.3.1 General

There are several alternative ways for estimating a design flood, with some having advantages over others in certain circumstances. The two most commonly used approaches for estimating a design flood at a particular site are:

- through the direct statistical analysis of the flood peaks recorded at a nearby gauging station on the same river, or by transposing the results of analyses of data from more remote sites draining areas with similar characteristics; and
- through the use of a flood event model such the Flood Studies Report (FSR) unit hydrograph rainfall-runoff approach, or by the use of a distributed, general runoff and streamflow routing model such as RORB (Laurenson and Mein, 1988).

The choice between these two types of approach is often made purely on the basis of whether only an estimate of the design flood peak is required, or if the detailed shape of the whole design flood hydrograph is needed.

2.3.2 Contents of the Flood Estimation Handbook

In late January 2000 the Institute of Hydrology, now renamed the Centre for Ecology and Hydrology (CEH), distributed the first copies of the Flood Estimation Handbook (FEH). The FEH contains the results of a five-year program of research supported by the Ministry of Agriculture, Fisheries and Food, the Environment Agency, the Scottish Office and the Northern Ireland Office. Although there are differences in content, character and emphasis, the Flood Estimation Handbook largely supersedes the Flood Studies Report (NERC, 1975).

The FEH, which is intended to provide clear guidance to those concerned with rainfall and flood estimation in the UK, consists of the following volumes:

- Volume 1 – Overview;
- Volume 2 – Rainfall frequency estimation;
- Volume 3 – Statistical procedures for flood frequency estimation;
- Volume 4 – Restatement and application of the FSR rainfall-runoff method; and
- Volume 5 – Catchment descriptors.

Chapter 5 of Volume 1 of the FEH provides guidance on the various factors influencing the choice between the statistical and rainfall-runoff approaches to design flood estimation.

Use of the FEH is supported by three software packages:

- The FEH CD-ROM that provides digitally derived catchment descriptors for any drainage area greater than $0.5km^2$ in mainland Britain and Northern Ireland and also implements the rainfall frequency estimation procedure contained in Volume 2;
- WINFAP-FEH which facilitates the application of the statistical procedures of Volume 3; and
- The Micro-FSR package designed for the Flood Studies Report (FSR) unit hydrograph rainfall-runoff method.

2.3.3 FEH CD-ROM

The FEH makes use of new catchment descriptors derived from digital data sets. Among the descriptors given are drainage area, average annual rainfall for the standard periods 1941 to 1970 and 1961 to 1990, and urban extent in 1990 as derived from satellite data.

Use of the CD-ROM should help to minimise errors in defining catchment characteristics, which were common with the manually derived values obtained from Ordnance Survey maps and the maps in Volume V of the FSR. It should be noted, however, that the Institute of Hydrology digital terrain model (IHDTM) is based on 1:50 000 scale mapping and that, for some areas, the generation of IHDTM-drainage paths is flawed. For these areas, the IHDTM may provide a catchment area that differs significantly from the area enclosed by the topographic boundary drawn manually from the pattern of contours on 1:25 000 scale Ordnance Survey maps. It is therefore advisable to confirm that the topographic boundary obtained from the digital data adequately portrays the study catchment.

The boundaries of small catchments (*ie* less than $5km^2$) are most prone to error, and especially so when urbanised. Fenland districts are also particularly difficult areas, and in some cases detailed local knowledge may be required to ascertain the direction that floodwater will drain.

2.3.4 Design rainfall estimation

Volume 2 of the FEH provides a new generalised procedure for obtaining rainfall depth-duration-frequency estimates for mainland sites in England, Wales, Scotland and Northern Ireland plus sites in Anglesey and the Isle of Wight. The new procedure, which is implemented by the FEH CD-ROM, provides design rainfall estimates for durations of up to 8 days and for return periods of up to 10 000 years. The CD-ROM can also be used to estimate the return period of a recorded rainfall event.

Overall, the new procedure represents an advance on the corresponding rainfall estimation methods provided by the 1975 Flood Studies Report; partly due to the improved data analysis and mapping techniques employed and partly due to the larger database of rainfall records now available. The FEH rainfall frequency estimates show greater local variations, with increased depths in parts of southeast England, the east midlands and western upland areas. Figures 11.7 and 11.8 of Volume 2 of the FEH are maps that show the ratio of FEH to FSR 100-year rainfall estimates for durations of 1 hour and 1 day.

It should be noted, however, that the FEH depth-duration-frequency model was fitted jointly:

- to selected durations between 1 hour and 8 days, and
- to return periods between 2 and 1000 years.

Outside these limits the rainfall estimates provided by the FEH CD-ROM should be used with caution, as they may prove to be less reliable. For example, the 10 000-year rainfall estimates provided by the CD-ROM, for many areas of England and Wales, are larger than the corresponding Probable Maximum Precipitation estimates contained in the Flood Studies Report (Babtie, 2000).

2.3.5 Statistical methods

A statistical approach is usually employed where only an estimate of the design flood peak is required. For sites close to a gauging station with a long-term record it has long been common practice to base the design flood estimate on the results of a flood frequency curve derived from an analysis of the recorded annual maximum flood peaks. A number of PC-based software packages are available to perform a frequency analysis using annual maximum flood flows, including WINFAP marketed by the Institute of Hydrology.

Chapter 15 of Volume 3 of the FEH provides up to date guidance on the choice of statistical distribution and fitting procedure.

The flood frequency estimates obtained from the analysis of the gauging station record can be transposed to the site of interest by scaling the flood estimates by the ratio of the respective catchment areas.

The flood peak data sets used in the research for the FEH Volume 3 are included on the flood data CD-ROM and are also supplied with WINFAP-FEH. The FEH CD-ROM displays the sites of the gauges to help with the location of potential donor catchments. These data sets provide a very convenient data source, but the annual maximum data series for the 1000 stations listed have a typical end date of 1993/94 and the peaks-over-threshold series have a typical end date in the 1980s. Where possible, data series should be extended/updated before use. It is also important to check locally for additional gauged catchments not in the FEH flood data sets.

Unreliable flood estimates are likely to result:

- if incorrect flood peak data are used, possibly due to an inappropriate flood rating curve for the gauging station;
- if there are significant differences between the characteristics of the gauged and study catchments; or
- if the return period of the design event is more than twice the length of record analysed.

The statistical approach recommended by the FEH is to construct the flood frequency curve as the product of the index flood Q_{MED} (*ie* the flood with a return period of 2 years) and the flood growth curve.

The choice of method for estimating Q_{MED} depends on the length of gauged record available. If there are more than 13 years of record the FEH recommends that Q_{MED} is computed directly from the recorded annual maximum flood peaks. For shorter records Q_{MED} should be computed from peaks-over-threshold data.

If only a few years of data are available, the estimate of Q_{MED} should be adjusted for climatic variability, which can result in some periods being particularly flood-prone, by correlation with comparable catchments in the general area with longer term records.

Estimates of Q_{MED} can also be made by transposing data from hydrologically similar gauged catchments, referred to as ‘donor’ or ‘analogue’ catchments, depending on their geographical proximity to the site of interest.

For those sites for which no local flood peak data are available, Q_{MED} may be calculated from regression equations that use values of catchment descriptors provided by the FEH CD-ROM. The equations recommended by the FEH for a wholly rural catchment are listed in Section 3.3 of Volume 3. For partly urbanised catchments, the rural value of Q_{MED} needs to be adjusted using the equations set out in Section 9.2.3 of Volume 3. It should be noted that these calculations, which can be carried out automatically within WINFAP-FEH, provide estimates for Q_{MED} that tend to be less reliable than those based on local flood data.

To derive flood estimates for return periods other than 2 years, it is necessary to construct a flood growth curve. In FSR methodology, there were fixed flood growth curves for specified Hydrometric Areas. The FEH advocates a more flexible approach whereby a flood growth curve is tailored to the site of interest, based on an analysis of the pooled annual maximum data for hydrologically similar gauged catchments. Catchment similarity is initially judged in terms of size, wetness and soils as represented by the descriptors AREA, SAAR and BFIHOST.

Routines within WINFAP-FEH can provide an initial pooling group of gauged catchments whose annual maximum flood data can be analysed to provide a growth curve for the site of interest. Some stations may need to be deleted from this initial pooling group if it is strongly heterogeneous, while other stations may need to be added to ensure that there are sufficient years of record to adequately define the growth curve up to the target return period.

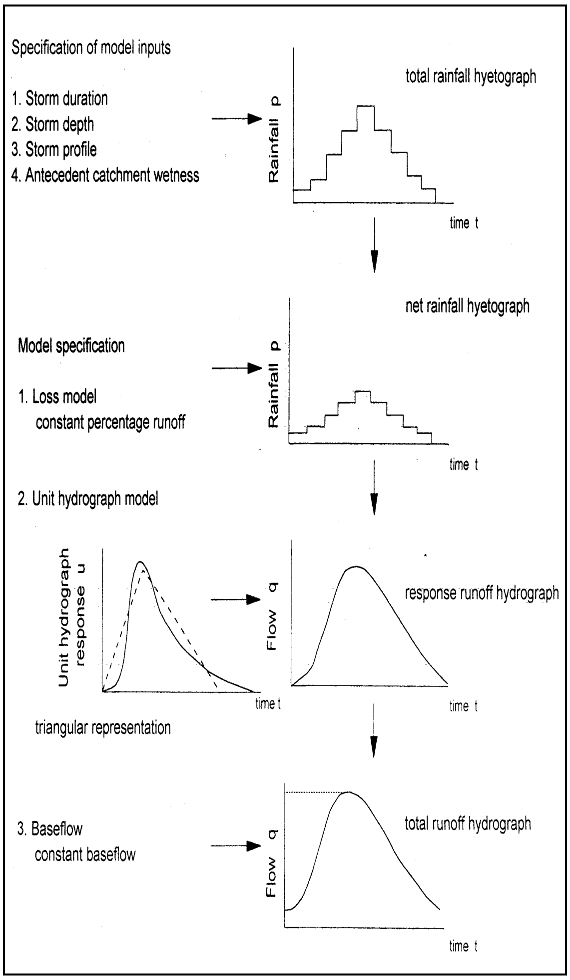
For partly urbanised catchments, the as-rural growth curve needs to be adjusted for urbanisation using the equation given in Section 9.2.4 of Volume 3. This adjustment is carried out automatically within WINFAP-FEH.

2.3.6 Rainfall-runoff methods

If the complete design flood hydrograph is required for a study catchment, then this is most often calculated using the FSR rainfall-runoff model. The figure opposite illustrates the main steps in the FSR unit hydrograph rainfall-runoff method. In summary, a design storm rainfall profile is converted to a flood hydrograph using a deterministic unit hydrograph and losses model. The main steps in the approach are:

- construct a total rainfall hyetograph for the design event;
- assess the proportion of rainfall which contributes directly to the flow in the river (constant percentage runoff);
- determine the catchment response to effective rainfall (NB the unit hydrograph shape is dictated by the time-to-peak); and
- calculate the quantity of flow in the river prior to the event (baseflow).

Volume 4 of the FEH provides a comprehensive technical rewrite of the FSR unit hydrograph rainfall-runoff method incorporating the numerous enhancements contained in 18 Flood Studies Supplementary Reports and other relevant research published in the Institute of Hydrology (IH) Report series, various technical journals and conference proceedings. Whilst the basic unit hydrograph rainfall-runoff methodology is not greatly altered from these earlier publications, some of the model parameter estimation equations have been updated in the FEH. Tables B.1 to B.3 of Volume 4 of the FEH summarise the various changes to the model parameter estimation equations and provide the details for the equations currently recommended.



Flood estimation using the FSR rainfall-runoff method (copied from Volume 4 of Flood Estimation Handbook)

The FSR unit hydrograph rainfall-runoff model may provide only coarse flood estimates, particularly when key model parameters are derived from catchment descriptors rather than local flood event data. For example Boorman *et al* (1990) showed that with estimates of unit hydrograph time-to-peak (*Tp*) and catchment standard percentage runoff (SPR) based on catchment characteristics, the mean annual floods of a sample of 74 gauged catchments were overestimated by 22% on average, and the 25 year floods by 41%.

The FEH team did not attempt to recalibrate the FSR rainfall-runoff model. Wide discrepancies have been found to exist between the flood peak estimates obtained when both the FSR rainfall-runoff model and FEH statistical approach are applied to smaller catchments and no local data are used. Whenever possible, actual flood event data should be used to provide more reliable estimates for the time-to-peak of the instantaneous catchment unit hydrograph and for the parameter SPR. Appendix A of Volume 4 of the FEH which lists the UK Flood Event Archive (Houghton-Carr & Boorman, 1991) is an excellent source of these data for over 200 stations listed.

2.3.7 Other considerations

Different sites within a river basin will be sensitive to different flood events. It is impractical, therefore, to construct a design event that will yield a flood of fixed rarity at all sites within a basin.

Extensive urbanisation has a marked effect on catchment flood behaviour. The increase in the amount of 'impervious' area and the decrease in storage capacity of a catchment present particular difficulties for accurately predicting flow. Experimental studies indicate that the gross effect of urbanisation is generally very marked at the small-catchment scale typical of many development-control applications. These studies have not been fully generalised, however, and it remains necessary to apply engineering judgement to assess the expected (gross) effect of urbanisation on flood runoff. The subject is considered in greater detail by Packman (1980), Hall (1984) and Hall *et al* (1993).

Flood flows can be significantly attenuated by storage in lakes and reservoirs, or on the floodplain. Such storage delays the timing and distribution of flood flows, so that the volume of water is discharged over a longer time period. A very useful review of UK experience in reservoir flood estimation is contained in IoH Report 114 (Reed and Field, 1992). Chapter 8 of Volume 4 of the FEH currently provides the most up to date guidance on the use of the FSR unit hydrograph method for reservoir flood estimation.

In many situations attention needs to be focused on flood volumes as well as flood peaks, to ensure that flood alleviation schemes are sufficiently robust to cope with multiple storms or long duration events. The direct analysis of flood volumes can sometimes provide valuable results, particularly for catchments larger than 500km^2 where major floods last for two or three days or more, and where the application of the FSR rainfall-runoff method becomes less valid.

Archer *et al* (2000) provide one approach to the analysis of flood volumes.

2.3.8 FEH guidelines

The Environment Agency is committed to the implementation of FEH methods where suitable and has issued guidelines (Spencer and Walsh, 2000) to assist Agency staff and its consultants to apply FEH correctly, including the systematic recording of the methods and data used.

Flood frequency estimates by whatever method are subject to change as methodologies evolve and as additional data become available. It is essential that engineers/hydrologists provide an audit trail of how they arrived at their final design flood estimate.

2.4 References

Topic	Reference
Basic hydrology	6, 17, 18, 19, 23, 24, 25, 26, 27
Estimation of mean flow	4, 5, 6, 13, 14, 15, 17, 18, 19, 23, 24
Flood estimation	1, 2, 3, 4, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 20, 21, 22, 25

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3. RIVER HYDRAULICS

3.1 Scope of the chapter

This chapter describes the hydraulic design and analysis of natural and artificial channels and the structures found in such channels. The object of this design is to determine how flow conditions (water depth, flow velocity and sediment movement in particular) are related to the discharge and the physical characteristics of the channel or structure.

3.2 Basic concepts

This section covers the basic concepts behind river hydraulics, including the forces and energy involved, the laws of continuity and 'control'.

3.2.1 Forces

The most important forces acting on flow in open channels are gravity and inertia. The ratio of these forces is represented by the 'Froude number' (*Fr*) which identifies the flow as being either:

- *subcritical* (as in a deep, slow-moving river), for which $Fr < 1$; or
- *supercritical* (as in a steep chute), for which $Fr > 1$.

The identification of these two flow regimes is of fundamental importance in open channel flow computations.

3.2.2 Continuity

The total mass of water entering a channel reach also leaves that reach, in one form or another. In most practical problems, compressibility and temperature effects (including evaporation) can be ignored, so the total volume of water entering a reach must also be the same as that leaving it.

3.2.3 Energy level

The 'total energy', *H*, associated with a cross-section in an open channel can be expressed as:

$$H = Z + y + \alpha \frac{V^2}{2g} \qquad \textit{(Bernoulli's equation)}$$

where Z is the elevation of the bed relative to a given datum, y is the water depth (so that $Z + y$ is the elevation of the water surface), $\forall$ is a coefficient which depends on the velocity distribution in the cross section, often taken as 1, and V is the average flow velocity.

The total energy along a channel can be plotted as a line, which will always be above the line of the water surface. This is the level to which the water would rise in a pitot tube placed into the flow and facing directly into the flow at a point where the velocity is representative.

3.2.4 Critical energy

For a given discharge and energy level, the flow in a channel can be either slow and deep (subcritical) or fast and shallow (supercritical). There is, however, a minimum energy level at which this discharge can be passed through a particular cross-section. This is referred to as the 'critical' energy, and the corresponding depth of flow as the critical depth. Under critical flow conditions, the Froude number, $Fr = 1$. This marks the transition between supercritical and subcritical flow.

3.2.5 Control sections

In subcritical flow ($Fr < 1$) surface waves travel faster than the flow, so any disturbance can be propagated upstream. Conditions are therefore controlled by what happens downstream. In supercritical flow ($Fr > 1$), waves are swept downstream, so that control is from upstream. As a result, any structure or channel geometry which causes the flow to pass through critical depth acts as a 'control section', preventing the transmission past itself of any disturbance in the flow. An important feature of such controls is that the critical depth (and hence the energy level upstream) is defined solely by the discharge and the channel cross section. This enables a control section to be used as the starting point for the computation of flow profiles.

Common critical-depth control sections include weirs, flumes and drops in bed level. Other features, such as sluice gates, can also act as control sections. Control sections only operate as hydraulic controls, however, for as long as they remain 'undrowned': if they become 'drowned', the control moves further downstream. They are also not the only type of control. Water levels in an estuary, for example, are controlled by the tide, while uniform flow at 'normal depth' (see below) can be a convenient control for computational purposes.

3.2.6 Hydraulic jump

The transition from supercritical to subcritical flow is referred to as a 'hydraulic jump'. The characteristics of a hydraulic jump (location, length and stability of position) depend on a number of factors, including the Froude number of the upstream flow and the tailwater level provided by the downstream control. These characteristics can be determined by considering changes in momentum. Hydraulic jumps are generally highly turbulent and dissipate considerable energy. As a result, they are likely to cause considerable damage if they take place in unprotected channels, particularly if the material in the bed and banks is erodible.

3.2.7 Energy losses

Any flow along a channel is resisted by shear forces, or friction, acting on the wetted perimeter, and by the turbulence generated by irregularities, changes in size and cross-section and other obstructions in the channel. Overcoming this flow resistance results in a progressive loss of energy along the channel. Various formulae for determining this loss of energy have been developed, the most common being the Manning equation, which incorporates an experimentally derived roughness factor (Manning's '*n*') that can be related to the channel's physical characteristics. Manning's '*n*' is generally used as a 'lumped parameter', taking account of the effects of variations in channel cross section, as well as the surface texture. The Colebrook-White equation can also be used, but is perhaps more suited to lined channels with uniform cross-sections than to natural channels.

3.2.8 Uniform and non-uniform flow

Uniform flow occurs in a channel with a constant cross-section when the gravity forces just balance the resistance forces. Under these conditions, the energy lost along a reach is the same as the fall in bed level, with the result that the depth, cross-sectional area and velocity of the flow are constant and the energy line, water surface and bed are all parallel. True uniform flow rarely occurs in natural channels, due to irregularity of cross-section, and does not always occur in artificial channels, due to the presence of controls. The concept is important, however, as it defines a depth/discharge relationship and hence the state to which the flow tends to converge in a long uniform channel when no other controls are present. Uniform flow can therefore be considered in itself as a control.

In steady non-uniform flow the discharge is constant with time, but the depth varies along the channel. If the depth varies gradually, as generally occurs some distance from a control structure, the pressure distribution over the channel section can be taken as hydrostatic and the water surface profile can be calculated from the control to the point where flow conditions are approximately uniform. This 'backwater analysis' can be done by hand, dividing the channel into sections and using an iterative step-by-step method to carry the computation from one section to the next. When doing this it is important to proceed from a control where conditions are known in an upstream direction if the flow is subcritical and downstream if the flow is supercritical. The calculation is tedious, however, and many computer software packages are available to carry out such analyses. When using any package it is important to appreciate the assumptions on which it is based and the resulting limits of applicability: some packages are not good at representing particular hydraulic features such as bridges or transitions.

If the flow depth varies rapidly along the channel, the pressure distribution can no longer be assumed to be hydrostatic. This complicates the analysis, with the result that there is no general solution. Individual solutions to specific problems are available, however, generally based on a theoretical approach supported by experimental results.

3.2.9 Steady and transient flow

The above description assumes steady flow conditions, implying a constant or near-constant discharge (with time) along the channel. If the discharge varies rapidly, as can happen during the passage of a flood or during operation of gates, for example, 'transient' flow conditions occur. The analysis of these conditions is complex, needing to take into account such matters as the transfer of water from the main channel to storage areas and possibly dynamic effects. Advice from a hydraulic specialist should therefore be obtained.

3.3 Hydraulics of rivers and channels

There are, in effect, two problems to be addressed in the hydraulic design of natural and artificial channels. In existing channels the problem is to determine the discharge capacity and hence what water levels will occur with different flows. In new channels the problem is to determine the cross-section required to pass a given flow without the water rising to unacceptable levels.

In both cases, the overall approach is similar. The first step is to identify the control sections and likely flow régime (subcritical or supercritical) under the full range of conditions that will be encountered. It is important to note that control may move from one place to another as the flow changes and control sections become drowned out.

In most UK rivers, bed slopes are such that the flow is generally subcritical. Some rivers, particularly in hilly or steeply sloping areas, may have supercritical sections, separated by tranquil pools under low-flow conditions. During floods, the pools can be drowned out, so that the whole flow is nominally supercritical.

3.3.1 Flow resistance

The main difficulty with hydraulic calculations for channels is determining the appropriate roughness factor (Manning's '*n*') to represent the resistance to flow that will occur over the full range of discharges. If the flow remains within the channel (in-bank), factors affecting Manning's '*n*' include:

- the bed and bank material;
- vegetation, in the channel and on the bank;
- variations in cross-section, size and shape of channel;
- the frequency and sharpness of bends;
- silting, scouring and bed sediment forms;
- the degree of obstruction (bridge piers, log jams etc); and
- stage and discharge.

Seasonal variations can occur due to vegetation growth and die-back, while maintenance procedures can have a major impact if they involve significant dredging or weed-cutting. Guidance on the value of Manning's '*n*' is available from a number of sources, with Chow (1959) providing a useful set of photographs. The choice of '*n*' value is important as flow velocity and hence discharge, is directly proportionate to '*n*' value.

The situation is considerably more complex if the flow is out-of-bank because of interaction between the in-channel and over-bank parts of the flow (noting that out-of-bank flow can occur in an embanked river if the floodbanks are set back from the bank of the normal channel). This is particularly so if the channel meanders significantly, since at places the over-bank flow may be directed across the in-channel flow. The effective resistance to flow, and hence the conveyance/water level relationship, is very difficult to determine in such cases and it is advisable to seek specialist advice.

3.3.2 Sediment movement

Sediment can be transported in open channel flow either as 'bedload', which remains largely in contact with the bed and is carried forward by sliding or hopping, or as 'suspended load', which is maintained in suspension by turbulence for considerable periods of time and moves with practically the same velocity as the water. Some of the suspended load (the larger material) falls back to the bed at intervals, but very fine material is carried as 'washload' and is transported without intermittent deposition.

The size of the material transported in each mode depends on the flow velocity and the grading and erodibility of material on the bed and brought down from upstream. A large number of methods for predicting sediment movement have been developed (see, for example, Gomez and Church, 1989 and Fisher, 1995) but care is needed in their application. Some methods, such as those by Meyer-Peter and Muller, Bagnold and Einstein, cover only bedload, so are only appropriate where the mobile bed material is coarse, such as gravel and cobbles. Other formulae, of which the best known are the Ackers and White and the Engelund and Hanson equations, cover the total sediment load, so should be used where there is significant suspended sediment transport. Formulae covering only the suspended load are generally inappropriate for sands, as some of the sand generally travels as bedload. Methods of Arora, Raju and Garde and by Westrich and Juraschek are available for estimating silt washload.

Flow over a bed of widely graded material can result in the finer fraction being removed, leaving the surface 'armoured' with coarser material which is stable at that flow. If the flow subsequently increases significantly, this coarse material may become unstable and move, leaving the bed unprotected and resulting in very rapid erosion.

The movement of bedload in particular is intimately connected with the development and movement of bed features such as ripples and dunes in sand beds and riffles and runs in gravel beds. These features, which are transient and depend *inter alia* on the size of the bed material and the velocity and depth of the flow, can have a major impact on the effective roughness of the channel.

In all unlined channels, natural and artificial, the long-term rate of sediment transport depends on a wide range of factors, including the time distribution of flows, the slope and nature of the channel and the characteristics of the catchment. These matters are discussed in Chapter 1.

3.4 Hydraulics of river structures

As discussed earlier, the flow at structures generally varies rapidly (with respect to location), with the result that only in special cases can a purely theoretical result be obtained. Most solutions are therefore based on a theoretical approach supported by experimental results. Typical problems for which results are available include:

- flow over weirs and spillways;
- flow through constrictions and expansions, including past bridge piers;
- discharge through and over gates;
- flow through culverts and so-called 'inverted siphons';
- the hydraulic jump and energy dissipation;
- losses at bends; and
- the effects of steps, baffles and drops.

As always, it is important when applying these results to appreciate the range of conditions for which they apply. For particularly complex or unusual structures there may be no results available, in which case model testing may be necessary. Specialist advice should always be obtained in these circumstances.

3.5 Hydraulics of other features

The hydraulic analysis of environmentally sensitive features, such as meanders, bays, pools, riffle-pool sequences and fish spawning or nursery areas can generally be undertaken using the approaches described above. For some features, it may be necessary to ensure that the flow depth does not fall below a certain value or that the velocity lies within a certain range. This can often be achieved, since such requirements are generally established on the basis of naturally occurring conditions, but may not always be possible. If it is not, the advisability of imposing such a feature on the channel needs careful consideration.

The hydraulics of flow at river confluences, bifurcations and along parallel channels (around islands, for example) can be complex, but again are generally solvable applying the approaches outlined above. The main difficulty is often determining the division of flow that will occur when a channel bifurcates. Frequently this can only be determined by trial and error, balancing the head losses that will occur along the channels so that the energy levels in each are the same at the beginning and end of the section. The division may, of course, vary as the total flow varies.

3.6 References

Topic	References
Basic concepts	3, 5, 6, 9, 15
Hydraulics of rivers and channels	1, 10, 11, 12, 13, 16, 17, 19
Hydraulics of river structures	2, 5, 18
Sedimentation	7, 8, 15, 19, 20
Hydraulics of other features	4, 14, 21

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4. TIDE AND SURGE LEVEL PREDICTIONS

4.1 Scope of the chapter

This chapter describes the sources of available data and the methods of calculating design water levels at the downstream limit of the fluvial system, which are influenced by factors other than fluvial flow. These include both predictable, regularly occurring events, such as tidal variation, and random events, such as meteorological surges. Superimposed upon these short-term variations are longer-term variations, such as sea level rise and tectonic changes, which also have to be considered.

Many of the methods described here are common to both fluvial and coastal systems. Flood defences within the downstream reaches of a fluvial system, however, also have the further dimension of freshwater flow influencing the design level.

Downstream water levels can significantly affect the discharge capability of a river and hence upstream flood water levels. It is therefore important to understand fully the influence of one on the other.

River flow may be considered as a random variable, depending upon random rainfall events and the catchment characteristics. Tidal variation, on the other hand, is predictable and is independent of the factors affecting river flow. Meteorological surges are dependent upon the weather, which may or may not, depending upon locality, be related to the factors affecting river flow. The only way to relate all these variables is through the use of probability analysis and statistics.

The level of effort required in determining the relationships between the different variables, for any particular project, depends upon the locality of the project, the degree of acceptable risk and an assessment of the sensitivity of design flood level to changes in any, or all, of the parameters. In most cases, the accuracy of any prediction will be determined by the quality and quantity of data available, and the time (and budget) within which the assessment needs to be carried out.

4.2 Basic concepts

Downstream water levels are composed mainly of two superimposed parts:

- the tidal variation; and
- the meteorological surge.

Tides are produced by the gravitational interaction of all heavenly bodies with the earth, although the main influences for tidal movements are the moon and the sun. All the heavenly bodies, including the earth, move in regular, predictable orbits. Their influence upon each other and therefore upon the earth is also predictable and can be estimated to a high degree of accuracy for any time, either in the past or the future. The tide-producing forces have a repeating cycle of approximately 18.6 years. The relationship between astronomical force and the local tide for any particular place on the globe, however, has to be determined by on-site measurements.

Surges are produced by the passage of high or low-pressure weather systems, causing a lowering (negative surge) or raising (positive surge) of the water level respectively. The surge is therefore the difference between measured and predicted tide level. Meteorological surge is superimposed upon the astronomical tide. In theory, the surge peak can occur at any time within the tidal cycle, as the two are totally independent. This will be discussed further later.

In some cases, wind and wave 'setup' could also be relevant. Wind setup is a tilting of the water surface due to the action of wind stress on the water surface, resulting in a rise in water level at the downwind end of a water body and a fall at the upwind end. Wave setup is a rise in water level near a sloping shore, due to the conversion of wave energy to potential energy.

4.3 Water level predictions

Water levels have been measured and recorded on a systematic basis, mainly at ports, around the coast of the United Kingdom, for over 100 years. The data are held both locally at the port and centrally at the Institute of Oceanographic Sciences (IOS).

The quality and therefore useable quantity of data for any particular locality is highly variable, and reference therefore needs to be made to IOS at an early stage. Changes in measurement technology have led to the establishment of a series of 'A' class stations, which produce high quality continuous water level recordings, and other lower class stations which produce either intermittent readings or less reliable data. All coastal locations around the UK can however be related with sufficient accuracy for most projects to an 'A' class station. Localities within estuaries and within the fluvial system cannot usually be related with as much confidence.

If time permits, it is highly desirable to obtain measured water level data at the site, or sites, of interest for a period of preferably at least 28 days. If continuous recordings are not practicable, then intermittent readings at hourly intervals can suffice. For a small fee IOS will analyse the readings and relate the site to the nearest 'A' class station. The longer the period of record and the closer the time interval between readings, the more accurate the relationship between the site and the 'A' station is likely to be. The readings should be taken at times of low river flow; otherwise a longer period of record will be required, together with records of river flow.

Tide Tables are published annually, in four volumes, by the Hydrographer of the Navy, for a series of 'standard ports' around the world. These predict the time and level of high and low waters and a series of tidal parameters, depending upon the nature of the tide at that locality. Also included are factors to be added to or subtracted from the times and levels at the standard port to determine the corresponding data for various 'secondary ports'.

The tides around the coast of the UK are semidiurnal in nature; there are generally two high waters and two low waters each day, of approximately the same amplitude. Each tidal cycle lasts about 12.5 hours. The tides vary from day to day on a 'spring–neap' cycle of about 14.6 days. The 'spring' tides are of high amplitude, with low low-water levels and high high-water levels, whereas the 'neap' tides are of low amplitude, with higher low-waters and lower high-waters. Although the form of the tide is constant around the UK, the range of the tide is significantly different; varying from over 13m on spring tides off the Bristol Channel to 2.7m at Portland and 2.6m at Lerwick.

Offshore, the shape of the tide is approximately sinusoidal, but as it approaches the shore it is modified by shallow water effects as a long period wave. The distortion of the tidal curve is most pronounced within estuaries, as it is modified not only by the bed but also by the banks. The 'flood' (incoming) tide generally becomes shorter further up an estuary, with the 'ebb' (outgoing) tide being lengthened. The extreme case of this is the 'bore' formed during high spring tides in the Severn Estuary.

Surges are the variation between measured and predicted (astronomical) tidal levels. Minor variations occur most days, but the levels are generally within 0.2m of the predictions. Larger variations may be caused by a prolonged period of high pressure, causing a reduced tidal level (or negative surge), which can be of concern for ship navigation. For flood defences positive surges are of concern. These are generated by the passage of low pressure weather systems.

The effect of these weather systems varies around the coast of the UK. Maximum surges occur in the South East off the Thames Estuary, and are caused by low pressure systems passing to the north of Scotland and then down the East Coast, forcing a mass of water into the southern North Sea. The maximum surge with a return period of 50 years at this location is about 3m.

Extreme low pressure weather systems occur predominantly during the winter, so large positive surges are also a function of the season, with surges likely to affect flood defences occurring between November and February.

The shape of the surge is a function of locality and the speed and depth of the depression. They can vary from short, very intense events, when water levels are raised by 2 to 3m for a period of only a few hours, with the whole event over within 12 to 24 hours, to long duration low intensity events, when the water level is raised only by 0.5 to 1m, but for a period of three to four days. Either can be critical to the design of a flood defence. The former is likely to be critical closer to the estuary mouth or on the coast, whereas the latter could influence water levels a considerable distance upstream.

Although, in theory, astronomical tides and meteorological surges are independent, being caused by forces which are unrelated, there is evidence that surge peaks do not coincide with the time of highest high water, which would often be the worst design condition. The most likely reason is that, because the tide, and hence the tide plus surge, acts like a long period wave, it is influenced by shallow water effects, particularly shoaling and bottom friction. These tend to exaggerate surges occurring at lower water levels and to suppress surges at higher water levels. It is, however, generally good practice to consider surges and tidal level as totally independent, and to design for an adverse combination.

There is strong evidence that sea levels are rising worldwide. At present, the rise is of the order of 1–1.5 mm/year around the UK, although there are concerns that this may increase due to 'global warming'. Opinion is divided regarding the likely rate of rise. Guidelines have been issued by MAFF (now DEFRA) for various regions of the country.

During the last Ice Age, the north of the British Isles was covered by an ice sheet down to about a line between the Wash and the Bristol Channel. The land beneath the ice sheet was depressed and the south of England tilted upwards. Since the retreat of the ice, the land has been recovering, with the north rising and the south falling relative to the sea.

The combined effect of the geodetic change and the sea level rise is for the sea level in the south east of England to be rising relative to the land at somewhere in the region of 4–6 mm/year, whereas in the north of Scotland the sea is falling relative to the land by a similar amount.

4.4 Joint probability (tidal level and fluvial flow)

The probability of a particular sea level due to a combination of tide and surge can be computed by considering the two events as mutually independent. The result can then be expressed as a 'return period', which is the average time in years which elapses between events of equal, or worse, intensity. In terms of probability, the chance of, for example, a 50-year return period event occurring in any one year, is 2%.

With rising, or falling, sea levels, as discussed above, the return period does not remain constant when designing for a life of say 50 years to 100 years. Depending upon the relationship between design water level and return period, a sea level change of only 0.2m during the design life (for example, 50 years at 4 mm/year) can alter the 'standard of service' from the original 100-year return period upon scheme completion, to perhaps a 20-year return period or less by the end of the scheme's design life. Looked at another way, to achieve a standard of service equivalent to a 100-year return period at the end of a 50-year design life, may require an initial design to a return period of 500 years or even longer.

Although there is no direct correlation between meteorological surges and rainfall, both are caused by low pressure weather systems, so there is likely to be some degree of correlation. Surges are the direct result of low pressure, whereas fluvial flow depends upon rainfall runoff and the time delays inherent in the river basin, which may delay the peak fluvial flow to long after the peak of the surge. Each situation therefore needs to be assessed individually.

At the mouth of an estuary, tidal effects normally dominate for the design of flood defences, whereas in the upstream reaches fluvial flow becomes more important. In between, the two effects interact. The best method of predicting flood levels of varying return period along a river or estuary is to analyse data from a series of locations with long term water level records. Without those, the next best solution is a dynamic mathematical model of the system, proven against a series of known events. The model needs to be run for a number of different combinations of fluvial flow and tidal conditions of known return periods.

4.5 References

Topic	References
Basic concepts	1, 3, 6, 8, 9, 11, 12, 13, 14, 17, 18, 19, 20, 23, 24, 25, 26, 27, 28, 30, 31, 32, 33, 34, 37, 38, 39, 40, 41, 42, 43, 45, 46, 48
Water level predictions	2, 4, 5, 7, 9, 10, 12, 15, 16, 22, 29, 35, 39, 47
Joint probability	21, 29, 32, 36, 44

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5. DATA COLLECTION

5.1 Scope of the Chapter

This chapter considers the type of data that may be needed for a project and the problems that may encountered in its collection. Briefs for the collection of such data should be written to reflect the specification requirements of the projects.

5.2 Overall Approach

The following factors need to be taken into account when planning a data collection programme:-

- the availability, reliability and form of existing data;
- the accuracy and amount of the data required by the project;
- the cost of collecting the data; and
- the management, storage and use of the data after collection.

In general it is advisable to:-

- identify the need for data as early as possible;
- search for and use existing data wherever possible;
- design data collection programmes in detail;
- assess data handling requirements and consider the use of innovative handling techniques.

5.3 Data Sources

The Agency will often hold much of the baseline data required for a project. Other organisations will also hold useful information, however. The types of data held by different organisations are listed below.

Environment Agency

- rain gauge data
- river and tide levels
- river cross-sections and bank levels
- flooded area (section 105) plans
- observations by flood defence staff
- river flow data
- water quality data
- ecological data
- fisheries data
- sediment (including suspended sediment) data

Meteorological Office

- rain gauge data
- wind data
- evaporation data

Institute of Hydrology

- river flow data
- evaporation data

British Geological Survey

- geological maps
- geological memoirs
- borehole information

English Nature, RSPB, County Wildlife Trusts

- ecological data
- designated sites
- biological action plans
- amenity and recreation

Angling Clubs, MAFF, Sea Fisheries Committees

- fish species and stocks
- shell fish

Local Authorities, Countryside Commission

- aerial photography
- recreation and amenity
- nature conservation
- local heritage

Local Libraries, Historical Associations

- records of flooding
- historic land use

Ordnance Survey

- maps
- aerial photographs

National Monuments Archive

- aerial photographs (historic)

Water Companies

- abstractions and returns
- effluent discharges
- stormwater outfalls

Industrial Companies

- abstractions and returns
- effluent discharges

Port/Navigation Authorities

- bathymetry
- tidal records
- currents
- sediment movement and dredging
- ship sizes and constraints
- ship movements and pilotage

5.4 Data Management

Data management problems may include the sheer volume of the data, its format and consistency. Data management may be helped by:

- using standard data formats;
- storage of data in standard spreadsheets or databases, possibly linked to a GIS system;
- use of statistical checks on data consistency and trends; and
- archiving of data in open locations for future use by others.

When storing data it is important to include information about its source, date and scale of capture and reliability.

5.5 Topographic and Bathymetric Surveys

Traditional or innovative methods, including those below, should be considered, as appropriate to the project:

- traditional land survey techniques;
- ‘total station’ techniques;
- aerial photographs and photogrammetry;
- echo sounding;
- global positioning systems (used on land or water); and
- LIDAR (Laser Instrument Doppler Airborne Reconnaissance).

The national framework for Section 105 Flood Mapping has produced a number of standard survey and data formats. These represent best practice and should be considered for survey work.

5.6 Flow and Water Level Surveys

Much of the data on discharges and water levels will come from existing flow gauging stations. However, the accuracy and reliability of these stations should always be checked, as should the applicability of the data for the purpose intended. The measurements from gauging stations may be affected by vandalism.

There are often problems in recording maximum flood levels properly, as they are beyond the range of the equipment, so reliance may have to be placed on separate human observations. The rating relationships used to convert levels to discharges may also be unproven at the highest levels.

In some cases, where there is an adequate 'lead time' for a study, consideration may be given to the installation of new gauges. Such data would probably not be of sufficient duration for use in its own right, but may be useful for correlating with data at neighbouring stations with a longer record.

5.7 Water Quality Data

It should be remembered that significant local variation of parameters may be found in the field. Parameters should always be compared with 'textbook' values, and carefully reviewed, before assuming values outside the usual range.

5.8 Geomorphology and Sediment Data

Surveys of river geomorphology are discussed in Chapter 1. Sampling of bed sediments is relatively easy to arrange but meaningful information about sediments in motion is difficult to collect as much of the transport occurs only under flood conditions.

5.9 Asset Condition Surveys

Preliminary condition surveys will provide information about the superficial appearance of the asset but cannot examine conditions below ground or (normally) below water, The need for additional information should be considered carefully and it is recommended that, if there is any doubt, expert advice should be sought. Record drawings are invaluable but are not always available for older structures.

5.10 Environmental Baseline Investigations

Information for environmental baseline surveys should be identified through consultations carried out as part of the scoping process. Much of the information is generally available through the Agency or from external consultants. Sometimes it will be necessary to commission more detailed surveys.

5.11 Geotechnical Investigations

A sound understanding of local ground conditions is essential for good design. Site investigations should be properly structured and planned, with sufficient time allowed to carry out the tests needed and prepare reports, as set out in BS 5930. It is recommended that specialist geotechnical advice is obtained as set out in Reference 8. For many projects this will require the appointment of a geotechnical adviser with a minimum of 8 years relevant post charter experience.

5.12 References

Topic	References
Basic concepts	2, 3, 4, 5, 9
Specialist advice	1, 6, 7, 8, 10

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6. FLUVIAL MODELLING

6.1 Scope of the Chapter

This chapter covers the key factors involved in the computational and physical modelling of river systems.

6.2 Basic Concepts and Common Concerns

6.2.1 Types of model

Two types of model are available for modelling river systems:

- computational models, for reach and basin-wide analysis; and
- physical models, for detailed analysis of local hydraulic features.

6.2.2 Uses and concerns

Computational models enables the engineer to:

- consider basin-wide impacts of fluvial works;
- examine a wide range of design options in a short time; and
- achieve, in most cases, greater accuracy and confidence in the results.

Increased use of computational modelling has also introduced a number of concerns for the project manager, including:

- appreciating the simplifications and assumptions inherent in the methods;
- selecting the appropriate model to use for a project;
- understanding the results and their accuracy; and
- management and budget control of modelling specialists.

The use of physical modelling avoids some of these concerns, but adds others, including:

- understanding the physical scaling laws governing the design and operation of the model;
- limits imposed by the physical size of the model and the scale available;
- the time taken for model construction and testing; and
- the time needed for making revisions and repeating testing.

6.2.3 Calibration and verification

The accuracy of a model is generally examined through a process of calibration and verification. The model is first calibrated, using data recorded during a number of events covering the range of conditions for which it is to be operated. It is then verified using data from other, independent, events to show how well the conditions predicted match those that occurred.

When examining calibration and verification results the limitations and uncertainties inherent in the way physical reality is represented in the model must be recognised. Uncertainty in parameters such as hydraulic roughness, the accuracy of flow and level measurements or estimates and the variability of physical processes such as sediment movement, may all contribute to modelling inaccuracy.

6.3 Hydrologic Modelling

Hydrologic models include:

- statistical models, such as the methods presented in the *Flood Estimation Handbook*; and
- river basin models, which vary greatly in complexity, but all include a rainfall/runoff simulator and flood routing along river reaches.

Hydrologic models may be used to produce inflow hydrographs for a hydrodynamic model of a river system. They may also be used in isolation, for example to assess the effect of flood detention basins in a catchment.

6.4 River System Modelling

The primary types of computational models for river systems are:

- ‘backwater’ models, used for modelling short reaches of river, along which there is little flow attenuation and flood storage; and
- fully dynamic models, used for modelling larger and more complex river systems.

Such models are generally 1-D models, assuming depth-averaged and width-averaged parameters across a river section, or pseudo 1-D models, which allow a representation of out-of-bank floodplain flow. Many models have facilities for add-on modules to simulate parameters such as water quality and sediment movement.

The correct and early choice of model type and software is a vital part of effective fluvial modelling. The choice of model must consider:

- the project aims;
- the required accuracy of the model;
- the software available to the project team; and
- the budget.

Early design of the model is also required to direct the data collection exercise properly. The design must consider the above points, together with:

- the geographical extent of the model;
- the ‘scale’ (cross-section spacing) of the model and the law of diminishing returns in terms of increased data density;
- the boundaries of the model, which may need to coincide with gauging stations, weirs, or other well defined fluvial features; and
- calibration and verification locations and accuracy.

Data required for the model includes:

- topographic data for model definition;
- flow and level data for model calibration; and
- other parameters (e.g. water quality).

The modellers should be either consulted or responsible for deciding on the locations for the cross sections.

The accuracy of data, even from gauging stations, should not be assumed. Data collection is considered in more detail in Chapter 5. Inflow hydrographs, usually determined from hydrological studies, are also needed for model design runs. In many cases, urban stormwater and sewer flows also need to be included.

Building, calibration and verification of a model should follow directly from good design and data collection.

Model reporting must include assessment of the model accuracy, perhaps in the form of sensitivity analyses.

The national framework for Section 105 Flood Mapping has produced a number of standard guidelines and record sheets for river modelling. These represent best practice and should be considered for all work.

6.5 Estuarine System Modelling

Computational modelling of estuaries is generally similar to river modelling, but with the addition of a seaward boundary where the levels follow a tidal curve. Estuarine modelling may be required to provide a realistic downstream boundary condition for a fluvial model. In other cases the fluvial model may be extended into the estuary. Care must be exercised where an estuary is:

- wide, with significant flow variations across its width; or
- stratified, with significant stratification of saline and fluvial flows.

Additional model types are available for estuarine modelling, for simulation of the above conditions. These include 2-D models, either allowing horizontal or vertical variation of parameters through a cross section, and full 3-D models, allowing variation in both planes. It should be noted that such models are generally more difficult and costly to build and calibrate, the data requirements being greater.

6.6 Management of Modelling

Close liaison between management and modelling must be maintained, to integrate engineering, environmental and specialist modelling disciplines, and to prevent the modelling from becoming an end - however interesting - in itself.

Management concerns may be reduced by clear terms of reference, with early preparation of a detailed specification of the modelling tasks. This formalises the model objectives, design, software, calibration and verification, accuracy and reporting.

Cost estimates for modelling projects are often optimistic, overlooking the potential delays and problems with data, model or computer hardware that can occur. To some degree this may be inevitable in a competitive tendering environment, so should be taken into account in drawing up briefs and reviewing tenders.

It should also be recognised that the investigatory nature of computational modelling will often result in genuine difficulty in assessing time and cost budgets in advance.

Cost control may be improved by:

- detailed specification;
- ensuring the timely availability of all the data required; and
- regular liaison.

In cases where cost over-runs are threatened, it may be appropriate to re-examine and prioritise the project requirements to suit the cost constraints.

6.7 Physical Modelling

Physical modelling should be considered for the detailed examination of local hydraulic effects, such as at bridges, weirs, intakes and the like.

Physical models should be given to specialist contractors, who have appropriate laboratory facilities. These contractors include specialist modelling companies and universities.

Physical modelling contracts should be written to allow the management staff to visit the model and interact with the modelling team. Such visits can give them a better understanding of the hydraulic features than they may gain from the final modelling report. It may also be possible for managing staff to be actively involved in the model tests.

6.8 References

Topic	References
Hydrologic modelling	1, 4
River system modelling	2, 3, 6, 7, 8, 9, 10, 11
Estuarine system modelling	4, 5, 6, 7
Management of modelling	6, 7, 8, 9

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PART 2 DESIGN CONSIDERATIONS

7. GENERAL DESIGN CONSIDERATION

7.1 Scope of the Chapter

This chapter sets out matters to be taken into account generally when designing fluvial works for the Environment Agency. More detailed comments related to specific types of work are given in Chapters 8 to 12.

The chapter assumes that a 'project appraisal report', defining the purpose and function of the works in outline and supported by an 'environmental assessment', has already been prepared. For convenience, however, the chapter reference list includes guidance on both project appraisal and environmental assessment. It also covers the legal background to land drainage and flood defence responsibilities.

7.2 Design Process

Although all designs are different and every designer has a different approach, there are a number of common steps, given under the sub-headings below, which need to be carried out whenever a design is undertaken.

7.2.1 Review Purpose and Function

Circumstances may have changed since the project appraisal report was prepared, or other factors needing to be taken into account may be identified during detailed design. To ensure that the works are as required, their purpose and function need to be reviewed regularly, at least at the beginning and end of the design period.

7.2.2 Identify Design Issues

Operational and environmental issues should be identified in the project appraisal and environmental assessment reports, but again need to be reviewed. Issues requiring particular attention, either because they may not have been fully covered in earlier reports, or because they may affect - or be affected by - design decisions, include the following:

- the river bank or bed stability - whether the banks or bed of the river are likely to move and, if so, how this can be accommodated;
- access - during and after construction, by Agency staff, contractors and the public;
- construction methods - whether local conditions or the design concept constrain the methods that can be adopted (and *vice versa*);
- construction materials - what materials are available and acceptable, taking note of the effect they may have on appearance function and maintenance;
- operation - what constraints are placed on the design, by the methods or circumstances of operation;
- maintenance - how the works will be maintained and whether the design can be improved to simplify maintenance;
- post-project monitoring - what monitoring will be needed, how often it should be undertaken and how the results should be processed and recorded; and
- health and safety, which is discussed separately below.

7.2.3 Determine Data Requirements and Gaps

In almost all circumstances additional information is required before the design can be undertaken. This generally includes topographic survey and geotechnical investigations. Other information which may need to be collected could include water levels (high, low), local ecology/habitats, local archaeology and local materials.

7.2.4 Establish Design Criteria

Operational and environmental criteria again should have been established for the project appraisal and environmental assessment reports, but should be reviewed at this stage. Engineering criteria to be established include:

- design events - the events or combinations of events to be used to set the conditions to be designed for;
- hydraulic performance - including how this may vary under, for example, a range of

conditions (such as water depth and scour depth) likely to be encountered;

- stability - including normal and extreme operating conditions (design events) and abnormal combinations of circumstances;
- design life - how long the works are intended to last and the implications on the durability of the materials to be used;
- buildability - not necessarily covered by health and safety considerations. Ease of construction is more likely to produce a better end product.
- mode of failure - what will happen if the design criteria are exceeded.

This last item needs to be considered in the context of the whole river system and surrounding area, not just the works themselves.

7.2.5 Undertake Detailed Design

Design is an iterative process; undertaking a detailed design entails revisiting and reviewing each of the above items on a number of occasions, with the final review being the last step in the design process.

7.3 Health and Safety Considerations

Health and safety are prime considerations in the design of all works. This is given legislative backing in a number of directives, which arise from the Health and Safety at Work Act (1974) and the Management of Health and Safety at Work Regulations (1992). The Construction (Design and Management) Regulations 1994 apply to most construction works. The Regulations require the client to appoint a Planning Supervisor who has overall responsibility for co-ordinating health and safety aspects while the works are being designed. This responsibility includes ensuring that Health and Safety Plans and a Health and Safety File are prepared and handed over to the Principal Contractor when construction starts.

The CDM regulations apply to construction projects and everyone associated with them. They place duties on clients, planning supervisors and contractors to plan, co-ordinate and manage health and safety throughout all stages of a project.

7.4 Risk Assessment

All works must be designed to avoid, reduce or control risks to health and safety as far as is reasonably practicable. Risk assessments are an inherent part of safe design practice and are required under current Health and Safety legislation.

The Agency has recently produced a Risk Assessment report (1997) which is a useful introduction to the subject.

7.5 Expert Advice

Specific recommendations on the need for expert advice when designing different types of work are given in Chapters 8 to 12. The safe design of all works, however, requires a sound geotechnical understanding. It is therefore a general recommendation that a geotechnical adviser, with a minimum of eight years post-charter experience, be appointed for all civil design work. This accords with the ICE Site Investigation Steering Group proposals.

7.6 References

Topic	References
Design process	1, 2, 3, 4, 5, 6, 7, 9, 11, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26
Health and safety considerations	8, 10, 12, 13, 14, 15
Expert advice	3, 26, 27

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8. CHANNEL MODIFICATIONS

8.1 Scope of the Chapter

This chapter covers the design considerations involved in carrying out works to modify a river channel. These may involve works affecting the river banks alone, works altering the cross section of the entire channel, or - more rarely - the construction of a new channel, for example as a flood relief or cut-off channel.

8.2 Basic Concepts and Common Concerns

Rivers and river channels may serve a number of functions, which include:

- catchment drainage;
- conveyance of flow;
- conveyance of sediment;
- control of groundwater levels;
- habitat for flora and fauna; and
- navigation and recreation.

8.2.1 Two-Stage Channels and Floodplains

Rivers are commonly considered to comprise only the channel between defined banks. In the UK, it is generally found that flows in excess of around the annual average flood (approximately a two-year return period) exceed the natural bank height and flow across the floodplain. In the design of any channel modifications, consideration must be given to this out-of-channel flow.

Floodplain widths may be limited by man-made obstructions; in particular, many rivers are constrained between flood embankments. Environmental considerations may also favour the use of two-stage channels, with a defined low-flow channel and berms, and areas adjacent to the channel which become inundated only under moderate flood flows.

The designer must give detailed consideration to the different flow conditions, both within the main channel and at higher stages with overbank flow. Research in recent years has shown that the interaction between flow in the main channel and that on the higher berm or floodplain is complex, particularly in meandering rivers. For major channel modifications with great complexity to the flow patterns, recourse to physical modelling may be necessary.

8.2.2 River Morphology

River channels, except where provided with a hard lining (generally in urban areas), have erodible banks and bed. All natural river channels are thus mobile, changing both their plan form and their gradients, although the latter may be of very long-term scale. The concept of channel stability must be considered in the context of the scale of the life of the proposed works.

Rivers vary considerably in their behaviour and characteristics, from steep, braided watercourses transporting gravels, cobbles and even boulders, to meandering lowland rivers and estuaries, carrying silts and clay-sized material. In certain types of catchment, streams may be ephemeral. It is important that both the nature and régime of the length of river under consideration, within the context of the overall catchment and the processes at work in the particular location, are understood. Many problems associated with channel modifications result from an incomplete consideration of their potential interaction with fluvial morphology. Further details are given in Chapter 1.

8.2.3 Environmental Considerations

Environment Agency policy is that, almost without exception, all river channel modifications must sustain, improve or re-establish the natural habitats. Environment Agency policy actively discourages the culverting of sections of watercourses, although short lengths of culverts may be unavoidable in certain circumstances. Environmental and ecological considerations thus dictate much of the design of river channel modifications. Particular matters to be considered include:

- the use of natural river forms, such as meanders and associated varying channel cross sections;
- the maintenance or restoration of riffle-and-pool low-flow features in gravel-bed rivers;
- use of two stage shallow V cross sections to promote the establishment of appropriate vegetation; and
- the use of appropriate 'soft green' measures for bank protection, including traditional local methods.

8.2.4 Design Flows

Within the context of a natural river in a floodplain, there can be no single 'design flow'. The designer must consider the implications of low flows, moderate flood flows at about bank-full conditions, and high flood flows when the flow will be over-bank. In many cases, however, there will be flood defence considerations, when the defined level of service dictates the flood flow, which must not exceed the flood protection level. Generally, modifications to a river channel should be designed to be consistent with - or to lower the stage-discharge characteristics of - the existing watercourse.

A change in the flow régime, such as increasing urbanisation of the catchment or changes in low flow abstraction may also affect the régime and characteristics of the watercourse.

8.2.5 Channel Roughness

The greatest uncertainty in estimating the capacity of any new channel or modification to an existing river lies in the assessment of the channel roughness. This is a function of the materials of the bed and banks, and the extent, density and type of vegetation growth. The roughness thus varies with depth and flow. It is different in the main channel and on the floodplain and, as noted above, is affected by the interaction of flows between these elements. In sand-bed and gravel-bed rivers, bed forms can develop during a flood, and the roughness may be different on the rising and falling stages of the flood.

Vegetation roughness can be very difficult to assess and depends on the time of year and maintenance schedules, as well as the factors indicated above. Sensitivity analyses should be carried out to assess the effect of changes in roughness on any predictions of water level and velocities.

8.2.6 Other Matters

Other matters, which may need to be considered, include:

- the effect of dredging on the channel régime;
- the use of river training works, particularly on steep, unstable rivers;
- the effect of changes to structures, both upstream and downstream; and
- loss of flood plain storage and flow capacity by new works, for example, road embankments.

8.2.7 Matters Requiring Specialist Inputs

Specialist advice should be sought in the following areas:

- river morphology;
- sediment movement; and
- ecological and environmental matters.

8.3 References

Topic	Reference
Basic concepts	3, 4, 9, 10, 17
Environmental considerations	2, 3, 5, 6, 8, 10, 14, 15, 18, 19
River morphology	11, 12
Bank protection	1, 9, 10, 16
Channel roughness	1, 13, 20, 21, 22, 23
Specialist inputs	7, 11, 17, 22

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9. FLOOD STORAGE ARRANGEMENTS

9.1 Scope of the Chapter

This chapter covers the design of works to store flood flows, with the objective of reducing flooding further downstream. It concentrates on the hydraulic aspects of such works; the design of individual components is covered in other chapters.

9.2 Operation

Flood storage works are either 'on-line', in which the water is stored within the river channel and its floodplain, or 'off-line', in which the water is diverted from the river channel, stored in a separate area and subsequently released back to the river or another watercourse.

9.3 On-line Storage Works

The components of on-line storage works include:

- an impounding structure - generally an earth or concrete structure across the river and floodplain, behind which the water is stored; and
- a flow control structure - generally set in the impounding structure, to control the outflow from the storage area.

The flow control structure can be a fixed throttle (such as a flume or orifice), sized to have little effect on normal flows, but requiring a significant rise in upstream water level to discharge flood flows. Such arrangements also require an overflow weir or spillway to cater for extreme events, which would otherwise lead to the safe water level upstream of the impounding structure being exceeded.

Often, the control structure incorporates gates, which are normally left open, but are operated during floods to ensure that downstream flows do not exceed the design flow of the downstream flood defences. Again, the operation rules need to cater for extreme events, which could overwhelm the impounding structure. If this is likely to occur, the normal response is to increase the outflow and accept that some damage may be caused downstream; this damage would generally be less than that caused if the impounding structure were to fail in a rapid and uncontrolled manner. This assumption, however, needs to be examined individually for each case.

9.4 Off-line Storage Works

Off-line storage works generally comprise:

- an intake structure - diverting water to the storage area when the river flow or level exceeds a pre-determined value;
- a storage area - a reservoir separated from the river, formed either by low ground levels (natural or excavated) or by retaining structures (embankments and/or walls); and
- an outlet structure - returning water from the storage area to the river after the flood peak is past.

A gravity rather than pumped intake arrangement is normally adopted on economic grounds, as the inflow rates required are generally high and operation relatively infrequent. Weirs can be used and have the advantage of beginning to operate whenever river levels rise above a given value. They provide no control over water levels in the storage area, however, and need to be long, if a significant discharge is required for a limited additional rise in river level. For this reason, a gated arrangement is often used.

The storage reservoir generally lies within the flood plain and is isolated from it by purpose-built walls or embankments (the implications for reservoir design through the Reservoirs Act (1975) are raised later - in paragraph 9.5.5). The volume available for storage in the reservoir depends on the water depth that can be obtained, which is controlled by existing ground and peak flood levels. This depth is often limited, making it necessary for the reservoir to cover a large area. Choosing a site where the ground is low (either naturally or as a result of excavations, for example for gravel pits) increases the depth available but may mean that pumps are needed to empty the reservoir after the flood has passed.

The outlet may be by gravity (generally using gates), pumped or by a combination of the two (with gravity discharge initially, then pumping to drain the lowest sections). The outlet capacity depends on the volume stored and the time allowed for the system to be fully drained, noting that the standard of protection is reduced whenever the reservoir contains water. Emergency overflow arrangements are needed to protect the reservoir and these may form a major part of the facility if the inlet is uncontrolled.

9.5 Key Design Considerations

Some of the factors needing consideration during the design of a flood storage scheme are discussed below.

9.5.1 Flood Volume/Duration

The design of the scheme is controlled by the assumed flood volume and flood hydrograph shape rather than the flood peak. It is essential that the hydrological studies are carried out with this in mind.

9.5.2 Timing of Inflow

The storage volume available is generally only a small fraction of the total flood volume. It is therefore important that the scheme does not begin to operate too early, as the reservoir may then be filled before the flood peak is reached.

9.5.3 Control Arrangements

The scheme's performance during a flood is generally sensitive to the flood characteristics. Optimising the performance requires a sophisticated control system, which integrates level and flow data from the catchment upstream with conditions at the area being defended. A detailed understanding of the river system and its response during floods is needed, to set operating rules which will not be compromised during normal, extreme or emergency conditions.

The corollary is that the impact of the change in the overall behaviour of the river system needs to be examined and that changes may be required to the flood warning systems.

9.5.4 Consecutive Floods

If a flood occurs while the storage reservoir still contains water from a preceding flood, the standard of protection provided by the scheme will be significantly reduced. This can also happen if a flood has two peaks and the reservoir is filled during the first; the risk of such floods occurring needs to form part of the hydrological analysis.

9.5.5 Reservoirs Act (1975)

If the storage reservoir is capable of restricting more than 25 000 m^3 of water above the adjacent ground level, it is likely to come within the scope of the Reservoirs Act (1975). This places an obligation on the owner to have the reservoir inspected by a properly qualified person at regular intervals.

9.5.6 Impact on Local Flow Conditions

The scheme may cause rapid changes in flow conditions locally (near the intake, outlet or any overflow arrangements). This could cause unexpected effects (water level changes, scouring) upstream or downstream.

9.5.7 Public Safety

Public safety must be considered, particularly in remote locations or where there is recreational use of flood storage areas which are normally kept empty, including the need for early warning.

9.5.8 Public Health Considerations

Local public health must be considered especially in urban areas downstream of storm sewage overflows.

9.5.9 Planning Permission

The need for planning permission can be an important consideration.

9.5.10 Loss of Development Potential

Loss of development potential may give rise to substantial compensation claims.

9.5.11 Statutory Powers

The Agency has no statutory powers to operate reservoirs. Consideration must be given to the negotiation of resettlement or compensatory payments.

9.5.12 Impact of River Maintenance

Operation of the scheme is likely to be sensitive to small changes in water level and may therefore be affected if the river maintenance arrangements are altered, affecting the channel roughness.

9.5.13 Environmental Implications and Joint Use

The development of a flood storage scheme usually provides opportunities for environmental enhancement. Opportunities for recreational development are generally more limited, because of potential conflict with the flood defence functions.

Water quality needs to be considered where the flood storage scheme involves the creation of a permanent body of water.

9.5.14 Drainage of the Area

Consideration must be given to how the area can be drained, after the scheme has been implemented.

9.5.15 Visual Impact

The visual impact of bunds and walls in urban areas must be considered.

9.6 References

Topic	Reference
Basic concepts	1, 7
Storage works	4, 5, 10, 13
Key design considerations	2, 3, 6, 8, 9, 11, 12

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10. FLOOD WALLS AND EMBANKMENTS

10.1 Scope of the Chapter

This chapter covers design considerations for flood and earth retaining walls, flood banks and channel banks.

10.2 Basic Concepts and Common Concerns

10.2.1 Purpose and Form

Flood walls and embankments may fulfil one or more of the following roles:

- excluding water from an area;
- retaining water within an area;
- acting as part of a conveyance - as part of the channel conveying water past the areas being defended;
- retaining soil and water as part of:
  - a flood defence structure;
  - a channel bank; or
  - an ancillary structure, such as a bridge or road embankment; and
- serve a secondary purpose, such as a wharf or road.

The choice of appropriate structural form in a given case may be influenced by a number of factors, including:

- the purpose(s) of the wall or bank;
- aesthetics and the environmental setting - landscape and townscape;
- land availability and cost;
- geotechnical considerations;
- access for construction; and
- construction and maintenance costs.

10.2.2 Performance and Loading Criteria

Performance and loading criteria are as listed in Chapters 4 and 5 of the NRA's R&D Note 199. Particular design conditions, which need to be considered, include:

- extreme low water levels in the river;
- design flood conditions;
- maximum credible flood conditions (floods exceeding the design event may overtop the structure but should not cause collapse);
- reverse water loading, where this is possible after overtopping or where flood water is stored;
- maximum rate of drawdown and resulting maximum difference in water levels between one side of the structure and the other side;
- extreme eroded bed levels at the toe of the wall or bank in times of maximum flow;
- maximum current velocities; and
- conditions during construction.

10.2.3 Effects of Structures on River Hydraulics

New banks and walls should be designed to minimise scour and sedimentation, both at the site of the structure and elsewhere. Their effect on the flow and flooding characteristics of the river system should be assessed. The role of the banks and walls as components in the flood defence system needs to be fully understood.

10.2.4 Geotechnical Considerations

Flood banks and walls frequently have to be constructed in areas where the soils are weak and highly variable due to erosion and redeposition when river channels have changed their course and depth. Ground investigations need to be particularly careful and thorough. Interpolation between boreholes needs to be considered with great care. An allowance for anticipated settlement over the life of the structure may have to be made.

10.2.5 Continuity

Continuity of the flood defence needs to be maintained, both during and after construction. Details at each end of a new defence need to be designed to avoid outflanking or creating points of weakness.

10.2.6 Water Pressure Effects

Where there can be water level differences between one side of the bank or wall and the other side, the effects of water pressure transmitted to the lower side should be considered. Assessment of uplift should allow for a range of assumptions, particularly where cutoffs are used. For example the transmission of water pressure through sheet pile cutoffs may range from 100% to virtually nil. Where it is practicable, water pressure should be relieved by drains. Where that is not possible, the design should allow for the forces to be resisted.

10.2.7 Top Level

Economic, environmental and technical considerations affect the choice of top level for a flood wall or embankment. In general, the top level should be set at a figure, which allows for:

- the maximum stillwater level of the design event during the life of the structure;
- wave runup, which varies according to the exposure, fetch, local winds, and the details of the structure;
- maximum acceptable overtopping rate;
- construction tolerances;
- forecast local settlement before the structure is refurbished;
- regional long term changes in ground and water levels;
- freeboard to allow for errors or variations in the above estimates and for wear and tear until made good by maintenance;
- the function of the structure; and
- risks associated with high structures

The function is also relevant to deciding on the top level in some cases, such as if a flood bank acts also as a weir into a flood storage area, when the top level has to suit the operation of the flood storage system.

Economic considerations can affect the choice of design return period and hence the top level of a flood bank or wall.

10.2.8 Maintenance

Access for, ease of and cost of maintenance need to be considered at the design stage. Loads arising from maintenance equipment should be allowed for.

10.2.9 Environmental and Community Effects

The effects of the structure on habitats, conservation, landscape and townscape needs to be considered from the earliest stages in the project.

The introduction of a flood bank or wall in an urban area can cause problems for the adjacent properties with regard to security and privacy. It may also sever existing access routes, or introduce requirements for steps or ramps, affecting use by people in wheelchairs or pushing prams.

10.3 Particular Design Issues Affecting Structures

10.3.1 Sheet-Pile Walls

The following points should be considered in the design of sheet-pile walls:

- the design life, corrosion rates, areas of accelerated corrosion and methods of reducing corrosion;
- the economics of using high-yield steel-sheet piles;
- if the pile section is sufficient to withstand being driven;
- abrasion by sand and gravel in fast-flowing rivers or where wave action is possible;
- the dangers of using cantilever sheet-pile designs for all but the smallest walls;
- the safe design of tie-rods affected by settlement of backfill (allow for rotation at each end);
- the safe design of connection details of waling to sheet piles (allow for combination of tension and shear due to vertical loading from soil and live loads on waling);
- the safe design of self-anchored corners (diagonal tie-rods put high forces into the

walings, which must be transmitted through the structure into the ground);

- the sensitivity of the wall to erosion of bed levels in front of the wall, increase in backfill levels and increase in water level differences;
- the acceptability of its appearance; and
- drainage on the 'dry' side of the wall.

10.3.2 Gravity Walls

The following factors need to be considered in the design of gravity walls:

- the design life and control of corrosion in reinforced concrete walls;
- the need for and expense of cofferdams for some types of wall construction;
- the vulnerability of gabions to vandalism and corrosion;
- the need to prevent the passage of water under the wall; and
- drainage on the 'dry' side of the wall.

10.3.3 Flood Banks

The following points should be considered in the design of flood defence embankments.

- local availability of suitable material for the construction of embankments;
- the control of erosion on the front face, crest and back face (if liable to overtop);
- resistance to damage by burrowing animals;
- the control of seepage through and under the bank;
- adequate crest width to allow for access by vehicles;
- the need to restrict access to cows and other animals which cause damage to banks;
- the need to specify suitable vegetation on banks and to avoid growth of trees;
- the susceptibility of soil to cracking;
- the need to incorporate any public footpaths or bridleways; and
- drainage on the 'dry' side of the wall.

10.4 References

Topic	Reference
Basic concepts	2, 6, 9, 12, 16, 17, 19, 26, 28, 29
Design issues	1, 3, 4, 5, 7, 8, 9, 10, 11, 13, 14, 15, 17, 18, 20, 21, 22, 23, 24, 25, 27

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11. RIVER & CANAL STRUCTURES (CIVIL ASPECTS)

11.1 Scope of the Chapter

This chapter covers design considerations for the civil engineering aspects of the following control structures in rivers:

- weirs and flumes;
- gated structures (including barrages);
- intakes;
- bridges and culverts;
- siphons;
- locks and fish passes; and
- drop structures.

Trash is mentioned but trash screens are dealt with in Chapter 12.

11.2 Basic Concepts and Common Concerns

11.2.1 Purpose

The purpose of the structure must be defined at the outset of the design. A structure may fulfil one or more of the following roles and impacts must be identified at an early stage:

- flow measurement (e.g. weirs and flumes);
- flow conveyance (e.g. bridges, culverts and gated structures);
- sediment control (e.g. intakes);
- navigation (e.g. weirs and locks); and
- water level control (e.g. weirs and siphons).

11.2.2 Design Flows

The magnitude/return period of the design flood depends on the importance of the structure and what would happen if the flow were exceeded. Other criteria may apply to particular structures. An economic appraisal may be needed to identify the optimum design flows. In all cases, the structure's behaviour under a range of flows, from very low to very high, must be considered.

11.2.3 Afflux

Under even modest flow conditions, most structures raise water levels upstream, which may reduce the standard of flood protection provided. Any afflux, which is defined as the difference in water level across the structure, should therefore be minimised, consistent with the purpose of the structure. The effect of an afflux is to increase flow velocities through the structure.

11.2.4 River Training

River training works are often associated with structures. Training works may be required upstream (for example, to avoid outflanking) and downstream (for example, to lessen the impact of the structure on flow conditions).

11.2.5 Transitions

Specific works are required at most structures to provide a transition between the engineered and natural waterway. The objectives are usually to achieve smooth flow conditions, minimise afflux and reduce the risk of scour.

11.2.6 Safety

Safety is a key requirement, and all designs must consider all possible safety issues. Access arrangements, by land and water, are particularly important, including access for operation and maintenance and access by the public whether intended, accidental or even illegal.

11.2.7 Trash

The risk of blockage of the waterway and damage to the structure must be minimised, possibly with the use of floating booms and screens (see Chapter 12).

11.3 Types of Structure

The main types of river control structure are described briefly below and design considerations are set out in Table 1.

Weirs are generally used to control levels for navigation or abstraction, to measure flows or to limit saline intrusion. They usually comprise an approach transition, a structure for the water to flow across, an apron or stilling basin, abutments and a downstream transition. The crest level and shape depend on the purpose of the structure.

Flumes are generally used for flow measurement, having some advantages over weirs, particularly if sediment loads are high. They are not suitable for large flows or on wide, shallow rivers.

Gated control structures (including barrages) provide greater control of river levels over a wider range of flows than fixed weirs. They are, however, more expensive, generally require a power supply, have greater operation, maintenance and control needs and involve greater risks. In the UK, the term 'barrage' would usually be applied to a structure controlling tidal flows in an estuary.

Bridges comprise abutments at each side of the waterway, intermediate piers, if present, and the deck. Bridges require significant structural and geotechnical inputs to the design.

Culverts are covered channels or pipes. They have three components; an inlet transition, the culvert barrel itself and an outlet transition. Several flow conditions can occur depending on culvert slope, tailwater level, flow and inlet details.

Culverts can sometimes be difficult to differentiate from bridges. In general, culverts are longer in relation to their width and height, have lined inverts and do not have any intermediate supporting piers.

Intakes are used to abstract water from a river or other channel for public water supply, for industrial purposes, including cooling, or irrigation. An intake needs to be capable of abstracting the required quantity of water under all flow conditions, while minimising the intake of sediment or floating material and maintaining 'compensation' flows downstream.

Siphons are strictly devices in which sub-atmospheric pressures are generated to increase discharge. The full hydrostatic head between upstream water level and downstream tailwater level is utilised to increase discharge; flow velocities inside the siphon can therefore be quite high. Typically, they are provided in place of simple weirs. Modern designs provide close control on the upstream water levels over a wide range of flows by automatic regulation of the quantity of air allowed to enter the barrel. The hydraulic design requires considerable care to ensure correct performance, and there are structural complications and costs associated with the necessary curved internal profile of the barrel.

'Inverted siphons' (a misnomer, as the flow behaviour is not siphonic) are culverts which run full and in which the invert level drops below the bed level at both ends. This type of structure is occasionally necessary where a drainage channel has to pass under another low-lying watercourse, road or other service.

Locks are used to transfer boats and shipping from one navigable reach to another at higher or lower level. The components of a lock are the upstream and downstream gates, with supporting structures, the lock chamber and any transitions to the river or canal section. Locks in rivers are linked to a river control structure, which is generally a weir.

Fish passes may be required to facilitate the passage of fish past obstructing river structures such as weirs or barrages. The objective of their design is to provide a ladder or cascade of pools, with tumbling flow between them, that fish are able to climb without undue stress. Their design depends not only on the physical parameters of the site and river, but also on the type of fish for which they are intended.

Drop structures are similar to weirs in that they provide a location for energy dissipation, with some control over upstream water levels. A typical use would be on a river diversion, where excess energy from a reduction of the length of the natural channel must be dissipated in a controlled way.

Table 1: RIVER & CANAL STRUCTURES –CIVIL DESIGN ISSUES

Key • *Generally relevant* o *Relevant – some cases* ***KEY ISSUES***	Fixed Weirs	Gated structures	Culverts	Intakes	Flumes	Bridges	Locks	Siphons	Fish passes	Drop structures
Location, alignment & layout	•	•	•	•	•	•	•	•	•	•
Nature & characteristics of water course	•	•		•	•	•			o	•
Design flows: High	•	•	•	•	•	•	•	•	•	•
Design flows: Low	•	•		•	•			•	•	•
Waterway size	•	•	•	•	•	•		•		•
Afflux/upstream water levels	•	•	•		•	•		•	•	
Channel stability & river training	•	•		•	•	•			o	•
Transitions	•	•	•	•	•	•	•	•	•	•
Trash/screening	•	•	•	•				•	•	•
Access for operation		•		•			•		•	
Access for maintenance	•	•	•	•	•	•	•	•	•	•
Public access	•	•	•	•	•	•	•	•	•	•
Navigation	•	•		o	•	•	•			•
Visual impact		•				•	•			
Passage of sediment	•	•	•	•				•		•
Channel regrading	•	•								•
Scour & protection works	•	•	•		•	•		•		•
Gates		•	o				•			o
Discharge relationship/flow measurement	•	•	•	•	•			•	•	•
Seepage & piping	•	•	•				•			•
Uplift	•	•					•			•
Stability	•	•			•	•	•		•	•
Energy dissipation	•	•	•		•			•	•	•
Tailwater level	•	•	•		•			•	•	•
MATTERS REQUIRING EXPERT ADVICE										
River morphology	•	•		•	•	•				•
Assessment of design flows	•	•	•	•	•	•	•	•	•	•
Navigation requirement	•	•					•			
Passage of fish	•	•	•		•			•	•	•
Gate design		•	o				•			
Ecological & environmental impacts of structure	•	•	•		•	•	•	•	•	
Ecological & environmental impacts of construction	•	•	•	•	•	•	•	•	•	•

11.4 References

Topic	Reference
Basic concepts	3, 5, 6, 7, 8, 10, 12, 14
Types of structures	1, 2, 4, 6, 9, 11, 13, 14, 15, 16, 17, 18,

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12. RIVER & CANAL STRUCTURES (M&E ASPECTS)

12.1 Scope of Chapter

There are a number of types of river and canal installations and structures that involve plant and other mechanical, electrical and instrumentation equipment. This chapter covers such plant which includes:

- gates and gate operating equipment;
- pumping equipment;
- inflatable weirs;
- trash screens and booms; and
- fish deterrent devices.

In many cases such equipment involves the provision of electrical power, with either local or remote control and instrumentation.

Generally, specialist advice should be sought with regard to the design specification and choice of all such equipment, but it is important that the potential problems and requirements of the plant are recognised.

12.2 Power Supplies

Many installations require electrical power for operation, monitoring and control, auxiliary services, lighting etc. Generally this requires a link to the supply system, for which suitable expertise and advice must be sought. In some cases, emergency standby generation may be required, or direct diesel-powered operation of the installation.

For remote monitoring stations, solar-powered instrumentation should be considered.

12.3 Control and Instrumentation

Many installations now have partial or full automation, with telemetry and Supervisory Control and Data System (SCADA) systems giving remote control, monitoring of operation and notification of failures. Flood control systems may include automatic operation, controlled remotely from a central logic unit.

Instrumentation would typically cover monitoring of flows, water levels, gate positions, pump operating pressures and power consumption. More sophisticated monitoring of equipment performance is also available.

Consideration should be given to:

- the security of installations;
- accuracy and reliability requirements;
- lightning protection;
- the risks of flooding; and
- back-up systems for critical installations.

Consideration should also be given to the method of communication and its compatibility with existing facilities, including maintenance and spares arrangements. Methods include hardwired links, telephone and (increasingly) radio. The costs of optical fibre links are unlikely to be justified.

12.4 Types of Installation

12.4.1 Gates

Gates are an essential part of many installations and range from major one-off designs, specifically tailored to the particular requirements of a site, to small penstocks, sluice gates and flap valves, that can be purchased as standard items.

In the fluvial environment, gates are used for:

- river level control;
- flood release and storage control;
- drainage releases;
- tidal back-flow control; and
- navigation lockage.

There are many different types of gates, and the best choice for a site depends on its particular requirements with regard to:

- flow control requirements;
- operation and control (e.g. whether manual, remote or automatic, frequency, accuracy etc);
- maintenance considerations;
- visual impact;

- passage of fish;
- navigation requirements; and
- cost.

Other matters that must be considered in the design of the gate and its installation may include:

- safety to the public and to operation and maintenance staff;
- materials (strength, durability, impact on the environment, etc);
- methods of lifting and control;
- power supplies under both normal and emergency operation;
- ease of handling and maintenance;
- repair and maintenance of protective coatings;
- sealing requirements;
- suppression of flow-induced vibration;
- instrumentation and control; and
- traditional local types of gate and river control (e.g. the use of paddle and rymer gates on the upper Thames).

12.4.2 Pumping Plant

Pumping plant is most commonly required in this context for drainage control, but may also be used for flood alleviation and for water transfers. Most installations have plant permanently in place, but in some installations, mobile plant may be brought in and installed for a temporary purpose.

There are many different types and designs of pump and the choice must be determined with regard to:

- the pumping requirements - the ranges of head and flow, frequency of operation and duration;
- whether the installation is to be manned or automatic;
- the use or otherwise of submersible pumps;
- the use of weather-proofed pumps or the need for a building;
- the passage of sediment and trash;
- cost (both capital and recurring);
- reliability;
- ease of maintenance and replacement; and
- the need or otherwise for variable speed motors.

Particular matters to be considered in the design of a pumping installation include:

- the hydraulics of the sump and approach to the pump;
- the avoidance of swirl at the pump inlets;
- inlet screening both for trash and fish;
- access for operation and maintenance and possible provision of lifting equipment;
- flammable gases;
- ventilation;
- power supply (electrical, diesel or diesel-electric) including standby provision;
- control and instrumentation requirements;
- visual impact; and
- safety and security for both the public and operations staff.

12.4.3 Inflatable weirs

Inflatable weirs have not been widely used in the UK to date, but are increasingly found elsewhere. They may be used in place of a gated barrage where there is a need to minimise afflux during floods. They require a compressed air or pumped water system to inflate. Advice should be sought from the manufacturers regarding security and control requirements.

12.4.4 Trash Screens and Booms

Trash screens are used to prevent the passage of floating and semi-buoyant debris into locations, such as culverts, intakes and pumping stations, where it could cause a blockage or damage equipment. Similar structures are also used for other applications, including the control of fish movement from reach to reach and as security and safety grilles across culverts, siphons, intakes and outfalls.

Mechanically-raked screens are not common, but there are some occasions where they may be required to protect critical downstream culverts, bridges or waterways in sensitive locations from high trash loads. Generally, the raking mechanism would be a proprietary installation and advice should be sought from the manufacturers.

Considerations affecting trash screens and mechanically-raked screens include:

- vulnerability to blockage, particularly during times of weed cutting;
- frequency of clearing required;
- safety of operatives carrying out manual raking;
- security and public safety, including unauthorised access;
- access for vehicles to mechanically-raked screens, the size of skip employed and noise nuisance in residential areas;
- the proven efficacy of the selected design; and
- the risks of mechanical plant breakdown, hydraulic fluid spills etc.

In some locations a possible alternative to a trash screen, whether manually or mechanically raked, is a floating boom, which uses the water flow past it to direct the floating debris to one side of the watercourse, from where it can be collected and removed.

12.4.5 Fish Screens and Deterrents

The need for deterrents to fish entering intakes and their direction towards fish passes has encouraged the development of a number of types of device for use in the fluvial environment. These include:

- air bubble screens;
- acoustic devices;
- lighting; and
- current deflection devices.

The choice of type and its detailed design and siting requires specialist advice and is a function not only of the site geometry and flow régimes but also of the species of fish to be deterred.

12.5 References

Topic	Reference
Basic concepts	3, 4, 6, 8, 9
Type of installation	1,2,4,5,6,7,10,11, 12

Note: *No references for control and instrumentation are included in the list below. The technology is changing rapidly and any standard text presented now would be very quickly out of date.*

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