THE RIVER RESTORATION CENTRE
Working to restore & enhance our rivers

River Rehabilitation Guidance for Eastern England Rivers

For
The Environment Agency Anglian Region

November 2005

Prepared by Martin Janes, Karen Fisher, Jenny Mant and Laura de Smith

RRC, Silsoe, Bedford, MK45 4DT
rrc@theRRC.co.uk

Table of Contents

Table of Contents **2**
1 Introduction **4**
1.1 This Guidance 5
2 The River Restoration Centre **6**
3 Rehabilitation Projects and Hydraulic Modelling **9**
3.1 1D – ISIS, INFOWORKS, HEC-RAS, MIKE11 9
3.2 2D model (Telemac 2D, River 2D, SSIIM) 10
3.3 3D models (Telemac 3D, SSIIM) 10
3.4 Conveyance Estimation System 10
4 Restoration Techniques **14**
4.1 Range of techniques used within Eastern England 14
4.2 Increased flood level risk for rehabilitation techniques 16
4.3 Modelling for rehabilitation techniques 18
4.4 Case Studies 20
5 Narrowing **22**
5.1 Implications for flood levels and flood regime. 23
5.2 Impacts and risks 24
5.3 The need and requirements for modelling 24
5.4 Case Study; the River Rhee at Wendy 26
6 Riffles/gravel bed **30**
6.1 Implications for flood levels and flood regime. 31
6.2 Impacts and risks 33
6.3 The need and requirements for modelling 34
6.4 Case study; the River Waveney at Homersfield 37
6.5 Case study; the River Wensum at Bintree 41
7 Backwaters **45**
7.1 Implications for flood levels and flood regime. 45
7.2 Impacts and risks 46
7.3 The need and requirements for modelling 46
7.4 Case study; the River Rhee at Wendy 47
8 Reconnecting remnant meanders **49**
8.1 Implications for flood levels and flood regime. 49
8.2 Impacts and risks 49
8.3 The need and requirements for modelling 50
8.4 Case Study; the Little Ouse 51
8.5 Case Study; Shopham Loop of the River Rother (W. Sussex) 52
9 Replacing weirs **54**
9.1 Implications for flood levels and flood regime. 55
9.2 Impacts and risks 55
9.3 The need and requirements for modelling 55
9.4 Case study; the River Welland at Harringworth 57
10 Channel re-profiling **63**
10.1 Implications for flood levels and flood regime. 64
10.2 Impacts and risks 64
10.3 The need and requirements for modelling 65
10.4 Case Study; the River Rhee at Wendy 66
11 Willow spiling **69**

11.1 Implications for flood levels and flood regime. 69
11.2 Impacts and risks 69
11.3 The need and requirements for modelling 69
11.4 Case study; the River Brent Rehabilitation Project 71
12 Woody debris 72
12.1 Implications for flood levels and flood regime. 73
12.2 Impacts and risks 73
12.3 The need and requirements for modelling 73
13 Fencing 75
13.1 Implications for flood levels and flood regime. 75
13.2 Impacts and risks 75
13.3 The need and requirements for modelling 75
14 Using the CES for a combination of techniques 77
14.1 Case Study; The River Witham at Claypole 77
15 CES and staff training. 82
16 Summary 83
River hydraulics 83
Conveyance Estimation System 83
Rehabilitation techniques 84
Staff Training 84
River Restoration Centre Advice 84
17 Glossary of Hydraulic terminology 85
18 References 86

Appendix A. Techniques listing 87
Appendix B. Guidance manual information 90

1 Introduction

Eastern England's rivers are characterised by the generally flat landscape of the area. This flat landscape, good soils and sheltered climate has been intensively cultivated for centuries. As with many such areas of food production, land drainage has been paramount, to enable working of the soils. Where river systems have been modified to allow/maintain agricultural production, we often see a long history of changes.

In Eastern England, some areas, such as the Fens and Levels, have been modified to such a degree that it is often difficult to fathom the natural/original drainage pattern. For further information see the many texts relating to fenland agriculture and land drainage (e.g. Hawkins 2000, Clayton 2004).

River restoration/rehabilitation is a concept that involves understanding the natural system, looking at the changes that have occurred and working with natural processes to achieve some form of recovery to a fully (restoration) or partly (rehabilitation) working fluvial system. In the Eastern counties, the natural system is difficult to find or even predict, the changes are many and complex and the natural functions that would aid self recovery are limited (low slope and poor gradient, interrupted sediment transport, interference by man).

The majority of work that will be planned and undertaken in the Anglian Region of the Environment Agency for England and Wales will be rehabilitation and enhancement rather than restoration. However, given the generally poor state of the river systems, opportunities for improvement are plentiful and the benefits they bring are significant. Put within a strategy for the river catchments (such as Catchment Flood Management Plans (CFMP's) or the Water Framework Directive (WFD) River Basin Plans), catchment scale river restoration planning can help to maximise the benefits from limited funding in a well structured approach and incorporate opportunistic works as they emerge.

Many of the techniques available for river rehabilitation in the UK are applicable to Eastern England rivers. One set of techniques may have been used on an upland stream, but the concept be equally applicable to a low energy environment, albeit using different materials. For example, the generic technique of narrowing has many variations; from blockstone in bedrock rivers to low groynes in chalk streams.

Appendix A illustrates the range of techniques available and those applicable to lowland England.

Of course, some Anglian Region watercourses will exhibit special characteristics (chalk streams, ephemeral streams, artificial controlled drains, pumped systems, etc). It must be stressed that each should be considered carefully before rehabilitation/enhancement works are planned. The techniques should reflect the objectives of the project and must be tailored to the specific site. Poorly planned schemes tend to fail their objectives, reflect badly on the instigators, but also present the river restoration concept in a bad light (one of little thought and less scientific justification).

River restoration is not an exact science given the variables involved and the paucity of credible scientific appraisal. Planning is best done on the basis of broad assessment backed up with scientific proof where appropriate and necessary. Unnecessary expenditure on modelling and design, is wasteful of resources and may stifle the recognition of opportunities to make a significant enhancement to the environment. A happy middle ground should be sought where considered, risk-based assessment of possible options provides a basis for discussion of the need for further information.

River rehabilitation and enhancement of Eastern England rivers is already well established. Agency Fisheries, Recreation and Biodiversity (FRB) staff have delivered and are delivering significant habitat biodiversity gains through this work. As schemes become more numerous and complex, assessing their contribution to river basin management and restoration becomes more important.

Project managers will need to access greater resources of information and build internal expertise to aid understanding and justify the proposed works within the regulatory framework of the organisation.

1.1 This Guidance

This document provides stand-alone descriptions of the main generic techniques used in the rehabilitation of Eastern England rivers, their background and intention, effect on the river and surrounding land and possible issues that may arise. These descriptions are then supported by an assessment of the hydraulic implication of such structural works, the options currently available to model them and their appropriateness.

It is often the case that projects could be, or are, constrained by the hydraulic regime of the watercourse/site (channel capacity, flood levels, storage, flood risk management standard of service, etc). For this reason this guidance document integrates an appreciation of flows and modelling into all of the techniques and examples.

Where applicable, case studies are used to demonstrate the above techniques, their modelling and their usefulness. The guidance also examines the use of the new Conveyance Estimation System (CES) and how this can help to determine likely changes to river and flood flows for different techniques.

Though the guidance will necessarily be generic, the document will refer to many different publications, listed in table 1a, highlighting their use, availability and applicability.

Manual/Guide
MOT - Manual of River Restoration Techniques
NR&WH - New Rivers & Wildlife Handbook
ARM2 - Australian Rehabilitation Manual - Volume 2
WTT - WTT guide to improving trout streams
SCUS - Stream Corridor Restoration USA
WBPG - Waterway bank protection guide
SEPAF - Managing river habitats for fisheries
GRMF - Guidelines for rehabilitation and management of floodplain
FWMH - Farming and Watercourse management Handbook
RRTH - Restoration of Riverine Trout Habitats
HAHP - Handbook for assessment of hydraulic performance of environmental channels
RRSH - Restoration of Riverine Salmon Habitats

Table 1a. List of useful manuals and guides

	Format	Design drawings	Case studies
MOT	hard copy/web	YES	YES
NR&WH	hard copy	NO	YES
ARM2	web/hard copy/CD	YES	NO (some in text)
WTT	hard copy	NO	YES
SCUS	hard copy	YES/NO	NO (some in text)
WBPG	hard copy	YES	YES
SEPAF	hard copy	NO	NO (some in text)
GRMF	CD/hard copy	NO	NO (some in text)
FWMH	web	NO	NO (some in text)
RRTH	hard copy	NO	NO (some in text)
HAHP	hard copy/CD	NO	NO (some in text)
RRSH	hard copy	NO	NO (some in text)

Table 1b. Guide/manual format and content relating to techniques in table 4a

Table 1b demonstrates the need for an overview of publications, especially when seeking specific design ideas. Of the 12 listed only 4 have design drawing information though most give at least some examples of sites where works have been carried out. Of the four most useful texts, one (WBPG) is purely a bank protection manual. The remaining three are the restoration/rehabilitation guides from the UK; Manual of River Restoration Techniques (MOT), Australia; Australian Rehabilitation Manual (ARM2) and USA; Stream Corridor Restoration (SCUS). The other texts are useful and do provide good background information, explanation and specific details on hydraulics, habitat, landuse, etc. However, with a limited budget and limited reading time the three guides should be 'core' reading; two of these (MOT and ARM2) are available via the internet.

2 The River Restoration Centre

The River Restoration Centre (RRC), through National Contract 10379, provides advice to Environment Agency staff on river enhancement and restoration project scope and potential. Through this Agreement RRC has produced the following general 'guidelines' for the use of in-channel structures for river rehabilitation in Eastern England rivers. These principles are based on best practice and the understanding of how river restoration techniques affect the hydraulic performance of rivers, as well as the types of modelling available and when to use them. It should be stressed that scheme design and approval will still be a process of negotiation with the various consenting staff, but with additional sound argument, basic modelling interpretation and supporting information.

River Restoration Skills and Experience of the authors

Martin Janes has 12 years of experience of river restoration and rehabilitation, initially as Project Co-ordinator for the River Restoration Project Ltd, delivering two £1.4M river restoration demonstration projects on the Rivers Cole and Skerne. As manager of the River Restoration Centre for the past 7 years, Martin has advised on the rehabilitation and enhancement of over 130 river projects through out the UK, from small scale bank protection and biodiversity projects, to flood alleviation schemes.

Projects include:

- In-channel rehabilitation measures for the River Colne, Halstead FAS, EA 2005;
- Scoping and pre-feasibility of restoring 2km of the River Adur, W. Sussex, RDS, EA 2004/5;
- Technical advisor to the Project Board of the River Avon and Avon Valley Initiative and LIFE Nature bid for £1M+ for strategic restoration of the river Avon and its tributaries, EN, EA, W. Trusts 2003/5;
- Scoping and feasibility of the River Teifi Restoration Project, Wales, CCW 2003/5
- River Ythan LIFE project, river meandering demonstration site design, Ythan Partnership 2003/4
- Scoping study of burn rehabilitation projects on Orkney, SNH 2003.
- Design and supervision of the rehabilitation of the River Rhee at Wendy, looking at enhancement of the low flow channel within a reprofiled and increased flood capacity channel, Cambs, EA 2000/2002;
- Scoping, planning and design guidance for the River Brent Rehabilitation, Wembley, L.B. Brent 1999/2003;
- Engineering works supervisor for the River Cole Restoration Demonstration Project, Wilts. RRP 1994/7.

Karen Fisher has over 15 years of experience in hydraulic modelling of rivers and catchments. Within the last ten years many of those modelling projects have involved restoration schemes. The following projects show her experience in practical river restoration design projects and associated research projects which have incorporated hydraulic modelling:

- Design concepts of replacement riffles and hydraulic modelling for Fletching Mill, River Ouse, 2004/05;
- Development of roughness advisor and concepts for the Conveyance Estimation System. 2001/03;
- Hydraulic modelling for River Rother, Shopham Loop, 2003/04;
- Initial design concepts/feasibility studies for Monks Brook River Restoration, Teign/Bovey Diversion scheme 1998;
- River restoration project (RRP) Rivers Skerne and Cole – contribution to design concepts and hydraulic and hydrological advice and modelling 1995;
- Research into environmentally acceptable channels and the impact on hydraulic performance over a 7 year period 1990-1997;
- Post project monitoring of river restoration/rehabilitation projects: River Blackwater NI, River Cole, 1994;
- Experience in managing studies on rivers for flood alleviation which included environmental enhancement: Bourne Ditch at Windsor, River Avon, River Thames at Maidenhead. 1993/94.

Jenny Mant has 9 years experience as a fluvial geomorphologist both in the UK and southern Spain. She now advises on rehabilitation and enhancement projects throughout the UK.

Other experience includes:

- River Sediments and Habitats and the Impact of Maintenance Operations and Capital Works - Steering group - part 2 *Defra/EA (also involved with part 1 - Report EX4929* - 2005
- FRMRC (Flood Risk Management Research Consortium) Priority Research Package 8 Geomorphology, Sediments and Habitat - 2005

- SNIFFER (Scotland and Northern Ireland Forum For Environmental Research) Project MAR3729 Development of hydro-morphological improvement targets for surface water bodies - 2004
- Geomorphological guidelines on bankside erosion structures, River Camel cSAC. Environment Agency (Cornwall) - 2000
- *River Wey catchment geomorphological survey and assessment*. Report to the Environment Agency (Thames Region) - 2001
- Beverley Brook geomorphological survey and restoration assessment. Report to the Environment Agency (Thames Region) – 2000
- MEDALUS III project – EU framework 5 project Ephemeral flow in river channels; desertification implications - development of a morphological, vegetation and sediment changes in ephemeral streams 1999

Laura DeSmith has 2 years experience of river restoration and rehabilitation work, whilst working for the River Restoration Centre and completing an MSc in Environmental Water Management. Laura is now a Graduate Engineer for Halcrow. Projects include:

- SNIFFER (Scotland and Northern Ireland Forum For Environmental Research) Project MAR3729 Development of hydro-morphological improvement targets for surface water bodies, December 2004
- Scoping Study for an Environmental River Engineering Design Manual. R&D Technical Report WA5-060, November 2004

Involvement in the Conveyance Estimation System (CES)

Karen Fisher was involved on the scientific team, providing data and ideas for developing the Roughness Advisor and advising on the input for the CES. She was involved in the testing programme where eight rivers were used to test and verify the system. The software was launched in 2004 and Karen has used the software in her own research on "development and comparison of methods for improved hydraulic prediction for in-stream habitats" and on these guidelines for in-stream rehabilitation features in Eastern England rivers since that time.

Guidance for Eastern England Rivers

This work is based on the experience of the authors in the application of river rehabilitation and enhancement techniques across the UK and specifically in Eastern England. It combines the understanding of how systems can be restored and the impact that changes have on the flow dynamics, sediment dynamics, channel capacity and flood hydrograph.

The Techniques pages give an introduction to the proposed method, its application, implications for flood risk management and need for modelling. Local case studies are used to suggest how a broad understanding of the concept can be interrogated through the CES package to provide an estimate of its site specific applicability.

3 Rehabilitation Projects and Hydraulic Modelling

A large selection of information is available on individual rehabilitation and enhancement techniques, projects as case studies, advise from experienced staff and external expert groups. With a good local understanding of the issues and problems affecting a watercourse reach, potential solutions can sometimes be relatively straightforward. In addition to information on the structural component of the work, planning a small scale rehabilitation or enhancement project requires an assessment of the impact of the works to the flowing river system. All works will require consent by Development Control (DC) and Flood Risk Management (FRM) staff, on the issue of flooding and flood capacity. The interpretation of how potentially straight forward works will affect the hydraulic regime can be far from simple.

There are many different methods and models for investigating the hydraulics of channels and floodplains. These include one, two and three dimensional models. In order for Fisheries, Recreation and Biodiversity (FRB) staff to have an understanding of the need for, and importance and variety of, hydraulic modelling, the following overview has been included in this guidance.

3.1 1D – ISIS, INFOWORKS, HEC-RAS, MIKE11

One dimensional modelling is an established tool internationally for the design and assessment of flood risk management infrastructure on rivers. Most of the river modelling packages have their origins in the simulation of flood flows. These models are not necessarily suited to other applications although they can be used and the results interpreted to great benefit. The currently commercially available software packages used in England and Wales are ISIS, INFOWORKS, HEC-RAS and MIKE11. The most commonly used are ISIS and HEC-RAS. . The choice of method for representing the hydraulics and the computational procedures needs to be applicable for river rehabilitation.

One of the limitations in each of the 1D modelling packages is the assumption of a fixed value of Manning’s ‘n’ (channel roughness) for all flow depths. This assumption may not be valid, as the hydraulic computations may need a different value of Manning’s n for different ranges of depth associated with changing flow regime.

The 1D modelling packages can be used in a steady or unsteady state.

Steady state is where the modelling takes a “snap-shot” of the river reach at an instant in time. It therefore represents one condition of flow and cannot investigate something that happens over a period of time.

The ***unsteady state*** condition looks at how the flow varies over a period of time from a few days to a few years if required. This type of modelling requires the variation of the flow/and level over time to be input into the model at the upstream and downstream end respectively. It is useful to use this type of modelling when changes to how the water is stored on the floodplain over a period of flooding are to be investigated.

3.2 2D model (Telemac 2D, River 2D, SSIIM)

The one dimensional models look at the flow and water levels along a channel. Two dimensional models investigate the flow along the channel and ***across*** the channel. This therefore requires the channel to be split into a grid along and across the channel rather than just a section across the channel. The more detailed the grid, the more detailed the results in terms of velocity and shear stress distributions. Often the grid is on a 1m by 1m basis which requires a bed level at each of these points. The amount of data to be collected is therefore much greater than for a one-dimensional model and the computational power and time (equalling cost) required to model on a two-dimensional basis is much greater than for a one-dimensional model.

The times when a two-dimensional model may be useful for river rehabilitation are when detailed flow characteristics in terms of velocities and/or shear stress is required across the channel or around a structure such as a riffle, groyne or deflector.

3.3 3D models (Telemac 3D, SSIIM)

Three dimensional models represent flow along and across the channel and through the depth of the water column. They add a further level of detail, complexity, time and costs to modelling a situation. At each point on a typical 1m by 1m two-dimensional grid there will be several points modelled through the depth of water. This adds greatly to the computing power required and more data to calibrate and verify the model is required. The results from a 3 dimensional model give a very detailed picture of the primary and secondary flow currents and turbulence. In a river rehabilitation situation this could be of use for specialist situations where details such as the velocities through the water column or the shear stress distribution are required or the flow spilt through a porous groyne or a riffle. In the type of projects we are considering here this is unlikely to be the case.

3.4 Conveyance Estimation System

To manage its flood defences, the Agency and other authorities responsible for flood management require accurate information about the capacity of river channels and their associated floodplains. Past research has provided data on flows in straight compound and vegetated channels but a middle ground still needs to be found between academic findings and practical problem solving techniques.

In response to the Agency's vision for reducing uncertainties in the estimation of flood levels, a team of experts, led by HR Wallingford has developed a new Conveyance Estimation System. The new system is aimed at England, Wales, Scotland and Northern Ireland. The Conveyance Estimation System (CES) provides access to current knowledge and understanding to facilitate the estimation of conveyance. It incorporates:

- A 'Conveyance Generator' that estimates the channel conveyance capacity based on the channel geometry and roughness, which is suitable for in-bank and out-of-bank flow in all UK rivers;
- A 'Roughness Advisor' - a dual paper/software system using photographs of different types of vegetation to 'match' a roughness coefficient to the channel under investigation.

The CES software is a Windows based system which is easy to use and gives outputs which are helpful and informative to the user. Examples of how it can be used, and where it has been used in the Anglian region are given in this report.

The advantages of the CES are that with very small amounts of data a “picture” of the hydraulic performance of a reach can be established.

The data required are:
Cross-section survey (a depth, width and side slope at minimum),
Water surface slope (preferred), or
Bed slope.

The roughness can be estimated from a site visit, knowledge of the site and/or photographs combined with the use of the Roughness Advisor database. The information allows the relationship between depth of water in the section and the discharge to be established for a single section. This section can be duplicated, or another section surveyed to establish the backwater effect over a reach. More sections can be surveyed and used in the backwater to give a more detailed “picture”.

The amount of data required is small in comparison with the more complex 1D models. The CES is simple to use and can be used without extensive training. Half to 1 day is recommended, although it can be learnt and used with the aid of the help package within the software.

A detailed knowledge of hydraulics is not required to use the CES. It is more important, in the interpretation of the results, to have input from staff with experience and knowledge of hydraulics. This is an ideal model for FRB staff to use to give information on the results of changes to the channel. The outputs include depths, discharges and velocity profiles across the channel. The outputs will allow more informed decisions to be made based on calculations which can be carried out within a few hours. The outputs will highlight where the issues are and enable Flood Risk Management and Development Control staff to make informed decisions about areas which may need further modelling.

Table 3a summarises the data requirements, indicative costs, application and outputs for the models discussed above.

Model	Data required	Cost[1] (500m)	Practical application	Outputs
1D	Cross-section survey of river and floodplain at ~ 100m intervals in affected area of river and approx. 1km up and downstream, depending on channel slope. LiDAR data may be used for the floodplain. Details of structures and bridges across channel. Roughness data. Flow and rainfall information from nearby gauging stations if available. Boundary conditions – flow and stage relationship at the downstream end. Calibration data.	£5k upwards depending on length of river, complexity of issue and type of modelling – steady or unsteady state.	Widely used by FRM staff to model flood flows and the impact of changes to the hydraulic regime on these. Outside the remit of FRB staff.	Water levels and flows at each section. Flow/level hydrographs if unsteady state at each section. Longitudinal profile. Flooded outlines. Cross-section averaged velocities. Depth averaged velocities across the river are possible.
2D	Detailed topographic survey information in river and floodplain on a grid of at least 2m by 2m or more detailed. LiDAR data may be used for the floodplain. Details of structures. Roughness data. Flow and rainfall information from nearby gauging stations if available. Boundary conditions – flow and stage relationship at the downstream end. Calibration data	Over £15K	More detailed examination of the hydraulic stresses acting on a structure. Used in higher risk situations on large projects to investigate key areas in more detail. Beginning to be used on floodplains to look at flows around buildings. Also applied to research situations to model flow/structure interactions.	Water levels and flows at each node point. Flow/level hydrographs at each section. Longitudinal profile. Flooded outlines. Depth averaged velocities across the river.

[1] Costs are indicative and highlight the magnitude of probable difference between models. Cost will also vary with site and project requirements.

3D	As for 2D models but topographic data required for 3D grid (x, y and z). Calibration data required for 3D grid.	Over £30K	Very detailed studies of major complex and/or high risk river engineering schemes where data on the vertical component of flow is required. Can only be done for shorter lengths of river due to computational power required for 3D grid information. Also applied in detailed research situations.	Water levels and flows at each node point. Flow/level hydrographs at each section. Longitudinal profile. Flooded outlines. Velocities at each node point in the river giving a 3D velocity profile.
CES	Cross-section survey extending onto floodplain if required. Flow and stage data if available. Water surface slope or bed slope. Roughness data. Calibration data if available.	£0.5K to 1K depending on complexity of site	Can be used by FRB staff to provide an indication of the likely impacts of a project on the current river reach. Training is advisable.	Water levels and flows at each node point. Longitudinal profile. Depth averaged velocities across the river.

Table 3a. Summary information for 1,2 and 3 dimensional models and the Conveyance Estimation System

4 Restoration Techniques

4.1 Range of techniques used within Eastern England

The restoration techniques which are commonly applied to Eastern England rivers have been identified by Agency staff as:

- Narrowing (including deflectors);
- riffles/gravel bed;
- backwaters;
- reconnecting remnant meanders;
- replacing weirs;
- channel re-profiling;
- willow spiling;
- use of woody debris;
- fencing.

Table 4a lists the above techniques and where examples of each can be found in the popular texts. The table also states if the entry is a case study (stating what happened in the case of a particular project) or a more detailed generic set of guiding drawings (with descriptions, materials, approach and justification for use).

Restoration Techniques	Manuals /Guides	Case studies	Design drawings
NARROWING			
Current deflectors (including wing, multiple, straight deflectors and submerged vanes)	MOT	Y	Y
Narrowing with aquatic ledges	MOT	Y	Y
Narrowing through silt removal	NR&WH	Y	?
Narrowing using limestone blocks backfilled with excavated soil	NR&WH	Y	?
Narrowing of an over-widened channel using low cost groynes	MOT	Y	Y
Creating a sinuous low-flow channel in an over-widened channel	MOT	Y	Y
Planting water plants - narrow stream/protect banks	WTT	N	N
Traditional retards (a series of piles)	ARM2	N	Y
Pin retards	ARM2	N	Y
Brush retards	ARM2	N	Y
RIFFLES/GRAVEL BED			
Stone riffle/permanent riffles	MOT	Y	Y
	ARM2	Y	Y
Creation of gravelly shallows/natural riffle form	WTT	N	N
	ARM2	N	Y
	RRTH	N	?
	CD	Y	N
	HAHP	N	N
Boulder placement (fisheries)	WTT	N	N
Introducing gravel to inaccessible reaches	MOT	Y	Y
Restoring and stabilising over-deepened river bed levels	MOT	Y	Y
Raising river bed levels	MOT	Y	Y
BACKWATERS			
Creation of backwaters	MOT	Y	Y

	NR&WH	Y	?
RECONNECTING REMNANT MEANDERS			
Meander reinstatement	RRTH	N	?
	HAHP	N	N
Reconnecting remnant meanders	MOT	Y	Y
REPLACING WEIRS			
Stone riffle/permanent riffles	MOT	Y	Y
	ARM2	Y	Y
Creation of gravelly shallows/natural riffle form	WTT	N	N
	ARM2	N	Y
	RRTH	N	?
	CD	Y	N
	HAHP	N	N
Bifurcation weir and sidespill	MOT	Y	Y
Drop-weir structures	MOT	Y	Y
Rock ramp fishways	ARM2	Y	Y
Fish Passageway	SCUS	Y	Y
Diversion of a river valley	MOT	Y	Y
Clay lined river	MOT	Y	Y
WODDY DEBRIS			
Re-introduction of woody debris	ARM2	N	Y
CHANNEL RE-PROFILING			
Re-profiling channel margins	NR&WH	Y	?
Meander reinstatement	RRTH	N	?
	HAHP	N	N
New meandering channel through open fields	MOT	Y	Y
	FWMG	N	N
New channel meandering either side of existing	MOT	Y	Y
New meander in an impounded river channel	MOT	Y	Y
New meanders to one side of an existing channel	MOT	Y	Y
New meandering channel replacing concrete weirs	MOT	Y	Y
WILLOW SPILING			
Willow spiling	MOT	Y	Y
Willow mattress revetment	MOT	Y	Y

Key

Yes – Y, No – N, Written design criteria but no drawings - ?

Manual/Guide

MOT - Manual of River Restoration Techniques
NR&WH - New Rivers & Wildlife Handbook
ARM2 - Australian Rehabilitation Manual - Volume 2
WTT - WTT guide to improving trout streams
SCUS - Stream Corridor Restoration USA
WBPG - Waterway bank protection guide
SEPAF - Managing river habitats for fisheries
GRMF - Guidelines for rehabilitation and management of floodplain
FWMH - Farming and Watercourse management Handbook
RRTH - Restoration of Riverine Trout Habitats
HAHP - Handbook for assessment of hydraulic performance of environmental channels
RRSH - Restoration of Riverine Salmon Habitats

Table 4a. Restoration techniques common to Eastern England rivers and examples of information available

4.2 *Increased flood level risk for rehabilitation techniques*

Table 4b below gives a summary of the risks of increased flood levels and impacts associated with the different restoration techniques.

Types of techniques:	**Risk of increased flood levels**			**Impacts**
	High	**Med**	**Low**	
Narrowing locally <10% of channel			✓	Potential to affect conveyance. Risk directly related to extent of works.
Narrowing locally ~20% of channel		✓		
Narrowing locally >50% of channel	✓			
Riffles			✓	Potential to affect conveyance and roughness. Riffles should only raise low flow levels by <10cm, or crest height less than 20% relative to bank height. Should be drowned out by moderate to high flows.
Cobble riffles/Rock weirs/Cascades	✓	✓		Greater potential to affect conveyance and roughness. Structures that raise low flow levels by >20cm, or crest height greater than 20% relative to bank height
Gravel bed I [Infilling] (fills deep water channel up to original bed level)			✓	Applies where channel is over-deep relative to downstream depths and infilling seeks to increase velocity/reduce deep silty pools. Where gravel is not currently the dominant bed type.
Gravel bed II [Raise Bed & Water levels] Raises bed above original bed level and raises water levels		✓		Bed level raised above the original bed level therefore increasing water levels. Where gravel is not currently the dominant bed type.
Backwaters				No impact, minimal risk
Reconnecting remnant meanders	✓			Re-routing the flow will have consequences for water levels and flood inundation. Modelling should be an integral element of this type of work unless sound justification is provided.
Replacing weirs			✓	Unlikely to have an adverse impact on capacity. Risk usually low if riffles lower than existing weir (often is the underlying rationale for the works).
Woody debris			✓	Model in CES using change of roughness. Risk is dependent on extent.
Channel re-profiling		✓	✓	Low risk if cut significantly greater than fill. Use CES unless unsteady modelling

				required. Modelling can be used to show benefits.
Willow spiling			✓	Can change roughness on banks – use CES to see impacts. Assumes regular maintenance programme to keep under control.

Table 4b. Summary of impacts and risks associated with restoration techniques

4.3 Modelling for rehabilitation techniques

Types of techniques:	None needed	Hand calcs	CES	ISIS etc	Comments
Narrowing locally <10% of channel	✓		✓		Extent of modelling required is dependent on risk to property and extent of narrowing work done. For example if narrowing is less than 10% of channel width and overall reach length it is unlikely that modelling will be required as risk is low. In other situations CES modelling is recommended.
Narrowing locally ~20% of channel			✓	✓	
Narrowing locally >50% of channel			✓	✓	
Riffles	✓	✓	✓		For riffles (a low crest relative to the bank height) then either no modelling or perhaps a hand calculation based on a crump weir can be done to check levels upstream and backwater extent. For other features with a higher crest use CES or 1D models.
Cobble riffles/ Rock weirs/ Cascades			✓	✓	
Gravel bed I [Infilling] (fills deep water channel up to original bed level)	✓		✓		No modelling required for gravel put in locally, below or up to the original bed profile.
Gravel bed II [Raise Bed & Water levels] Raises bed above original bed level and raises water levels			✓		With gravel on a more extensive basis use roughness advisor in CES to look at water level rise.
Backwaters	✓				No modelling required
Reconnecting remnant meanders			✓	✓	Generally an unsteady state model required as objective of restoration is to get water back onto floodplain where water will be stored.
Replacing weirs	✓	✓	✓		Initially use hand calculation to show difference between upstream level for a weir and riffle.
Woody debris	✓		✓		Usually no modelling required other than when debris is significant when roughness advisor within CES could be used.

Channel re-profiling	✓		✔	✓	Use CES depending on extent of re-profiling.
Willow spiling	✔		✓		Modelling usually not required unless extensive

Table 4c. Guidelines for modelling restoration techniques

Table 4c gives a summary of the recommended[2] type of modelling required for the different techniques, if they are needed, based on the decisions made from considering table 4b. The suggested model is represented by a large 'tick' although the other techniques marked are also appropriate. The level of modelling required, or not, is dependent on the level of risk (table 4b). For narrowing there are several different options depending on the type and extent of narrowing. It may be that in a situation where the channel narrowing is <10% but the area where narrowing is being done is a high risk area, a rise in flood levels would cause an impact on say a residential area. In this situation, modelling should be done using the CES.

[2] It is important to stress that the level (if any) of modelling required has to be assessed for each individual case and these are recommendations and guidelines not fixed rules.

4.4 Case Studies

For the techniques discussed in this guidance, examples have been used to highlight the benefits and issues associated with each. Local sites were modelled as demonstration of the CES software within this project.

The sites chosen for modelling using the CES were as follows:
Central Area

- Little Ouse at Thetford;
- River Rhee at Wendy.

Eastern Area

- Waveney at Homersfield (a proposed site);
- Wensum at Bintree.

Northern Area

- Welland at Harringworth;
- Witham at Claypole.

This selection included one site where meanders were reconnected on the Little Ouse, a site where re-profiling and narrowing took place on the River Rhee, a site on the river Welland where a weir was replaced with riffles, two sites of different sizes where channel narrowing had been undertaken on the Wensum and the Witham. Riffles had also been incorporated at both sites on the Wensum and Witham. The remaining site on the Waveney is one where the restoration was being planned but had not yet been carried out. The proposal is to extend and add riffles and incorporate some berms along the reach.

The site discussions are based on a minimum amount of data, taken from a half day site visit to each location. There was very little information available for the sites pre-restoration so the data used in the modelling was based on qualitative information gained. The results give an indication of the impacts of the restoration but not necessarily an accurate prediction. The modelling is more to show the process of **how** the CES software can be used to show the impacts of in-channel restoration techniques on water levels and **what** information can be gained that will lead to better decision making.

The case studies are discussed within the appropriate technique section, to illustrate the general text.

River Rehabilitation Techniques

The following Sections (5 to 13) comment specifically on the following rehabilitation techniques. They give examples do demonstrate key points and refer to further information.

- Narrowing (including deflectors);
- Riffles/gravel bed;
- Backwaters;
- Reconnecting remnant meanders;
- Replacing weirs;
- Channel re-profiling;
- Willow spiling;
- Woody debris;
- Fencing.

Examples boxes:	**Yellow boxes provide a link to specific examples from the list of rehabilitation techniques in Section 4.**
Impacts and risks:	**Green Impacts and Risks tables for each technique are given, derived from the tables in Section 4**
Need/requirements for modelling:	**Green Need and Requirements for Modelling tables for each technique are given, derived from the tables in Section 4**
Data and Resources boxes:	**Blue boxes suggest the Data and Resources needed to assess each technique. The ‘🖫’ and ‘£’ symbols indicate data and resource requirements (scale of 1 to 5, with ‘(brackets)’ to show where more might be necessary.**

5 Narrowing

By widening rivers to increase flood capacity and in-channel storage, the biodiversity value of the river is often reduced and the flow patterns and sediment system altered. This often manifests itself as:

- reduced natural gravel bed material (through mechanical removal and smothering by silt)
- increase in bank slope angle and instability (mechanical widening);
- an increase in sedimentation (reduced velocities across the channel);
- increase in in-channel emergent vegetation and choking of the channel.

In order to attempt to combat these symptoms, narrowing by a variety of techniques can be used. The benefits being to;

- increase flow velocities and reduce sedimentation and excessive in-channel ‘weed’ growth (in some cases scouring the silt and sustaining a natural/imported gravel bed);
- reduce the low-flow width of the channel to provide a more appropriate channel dimension in low/normal flow periods;
- provide damp/wet marginal habitat where little often exists due to widening and continued maintenance operations;
- reduce costly annual maintenance works.

These physical benefits are able to provide direct biodiversity benefits to fish, invertebrates, macrophytes, landscape and public amenity benefits.

Narrowing can be achieved by two principle methods;

1. Physical narrowing of the river using infill and structures;
2. Altering the flow and sedimentation patterns to achieve deposition of silt and plant growth at desired locations.

The 1st is the most direct and easy to design and implement. It assumes knowledge of the river system and an understanding of the needs of that river to the degree that the designer can impose structure on the system. The narrowing is in place by the end of the works period.

Examples of narrowing using ‘infill’ structures

MOT – River Skerne (Aquatic ledges)
NR&WH – River Windrush (Coir fibre matting & Larch poles)

The 2nd is a more adaptive method, working with the flow and sediment regimes of the river. By correctly locating structures in a sediment laden reach, siltation can occur within days and marginal colonisation begins to formalise the feature within the growing season. The narrowing may take a year or more to occur and will be subject to flow variations (a flood could scour the feature away completely in the short term).

Examples of narrowing by encouraging deposition

MOT - River Avon (Low cost groynes)
MOT - River Skerne (Current deflectors)
ARM2 (Low deflectors)
ARM2 (Pin & Brush retards)
ARM2 (Retards)
ARM2 (Bendway Weirs)

Both methods are valid and have been employed throughout the UK on lowland systems. The 2nd is more suited to sediment laden rivers and can be a cheaper alternative with less materials and imported fill required.

5.1 Implications for flood levels and flood regime.

Narrowing will reduce the capacity of the channel (storage volume) and its conveyance (the ability of the channel to convey water), as the room available to transport water within the channel is reduced by adding the structures, accreting silt and promoting vegetation growth. A reduction in conveyance can cause a rise in flood level.

However, the main reason for narrowing is the over-sizing of the channel in the 1st place. It is implicit that for this suite of techniques early dialogue is held with flood risk management staff to ascertain the necessary capacity of the channel. If the channel is agreed as being over-sized then the works should be able to be accommodated. In this case the low flow levels will be increased, but the high flows (bank full) will be maintained within the channel to the desired standard of service.

If the narrowing is local then the rise may be minimal, a few millimetres in a flood situation. Modelling can be used to prove the case for narrowing if it is felt that the effect on flood risk will be limited. This is demonstrated in the example in section 5 below. In this situation the risk of increased flooding will be small.

If the narrowing is more extensive, over a whole reach of 100m or more, the risk of flooding may be greater and it will be necessary to check that the flood capacity remaining in the channel is not compromised. If such a proposed reduction in capacity is not supported by flood risk management, other combined measures may be able to offset the narrowing with for, example, re-profiling. Or alternative flood storage should be supplied elsewhere to reduce or mitigate the risk. As a practical “rule of thumb”, the volume of water using that part of the channel over a flood event needs to be replaced by a volume in flood storage.

There are some other risks associated with narrowing:

- velocities can be increased locally causing erosion;
- the water may pass through the narrowed reach more quickly and cause increases in flood levels downstream.

These need to be considered as part of the overall risk assessment in early option appraisal discussions.

If the narrowing is over a few metres or tens of metres in a reach of hundreds of metres then the impact of the above is likely to be minor. Once the narrowing is undertaken over a channel length >20% of the overall channel then this may have more major implications on flood level rise.

5.2 Impacts and risks

Types of techniques:	Risk of increased flood levels			Impacts
	High	Med	Low	
Narrowing locally <10% of channel			✓	Potential to affect conveyance. Risk directly related to extent of works.
Narrowing locally ~20% of channel		✓		
Narrowing locally >50% of channel	✓			

5.3 The need and requirements for modelling

Types of techniques:	None required	Hand calcs	CES	ISIS/INFO WORKS	Comments
Narrowing locally <10% of channel	✓		✓		Extent of modelling required is dependent on risk to property and extent of narrowing work done. For example if narrowing is less than 10% of channel width and overall reach length it is unlikely that modelling will be required as risk is low. In other situations CES modelling is recommended.

If there are any concerns based on the impacts and risks described above, modelling can be undertaken using the Conveyance Estimation System to investigate the extent of change in water level.

If narrowing is over a reach of river or parts of the reach, then details of a number of sections, before and after narrowing should be modelled using the CES and the impact on the backwater profile investigated using this tool. This can be seen in the example on the River Welland in Section 9.

The CES is a **steady state** system (the flow does not vary with time) where water levels can be investigated over a reach length. This will enable the user to determine the change in water level at each section and over a reach.

Steady State (CES)

Data needed
cross-section topography (before the narrowing and after the narrowing)
a comparison of the stage discharge relationship of the two sections.

Resources £ £ £ £ £
The time taken to collect the data for cross-sections on a reach over a few hundred metres would be 1 day and then 1 day for analysis using the CES.

If the water level is predicted to rise to an unacceptable level due to the narrowing, then further **unsteady state** modelling may be required to look at complimentary storage options further upstream to take excess flood water.

The CES gives an indication of the scale of the problem which can be used to decide whether further modelling is required.

This would require an unsteady state model such as ISIS or INFOWORKS. The modelling of a scheme where flood storage was required could require a model of greater length, several kilometres, to investigate the impact of the changes upstream and downstream of the narrowed area. This would involve greater cost due to increased data requirements and modelling time.

Unsteady State (ISIS/INFOWORKS)

Data needed
The same cross-section data collected from the CES can be used in ISIS and INFOWORKS but it is advisable for the data to be geo-referenced for these models so that comparison with LiDAR or OS maps can be done. Contour surveys would be required to investigate the potential for flood storage.

Resources £ £ £ £ £
The survey information is therefore more complex and costly and would probably require an experienced survey team or external company. In addition to the extra survey work this would be a modelling exercise of several weeks depending on the complexity of the problem.

5.4 Case Study; the River Rhee at Wendy

The Rhee (Upper Cam) had been historically dredged at this site until the channel was very deep, wide and had little in stream variation. Banks were uneven, having a high left bank where years of dredgings/weed cuttings had raised levels.

Before. Nettle banks with dredgings levee. Steep sided bank. May 2001.

During. Nutrient rich dredgings and topsoil removed and piled behind track. Ledge formed by pushing toe forward – vegetation & roots intact. August 2002.

After. Bank grass seeding established. June 2003.

The river suffered from low flows in summer as there was little water over a wide bed area. Marginal growth was severely restricted by the management and lack of suitable substrate, exacerbating the over-wide situation.

One element of the scheme sought to narrow the low flow channel and create a damp/wet ledge for marginal plant colonisation. This was done by 'pushing' the toe of the clay bank (complete with vegetation) forward and downward (Figure 5f).

This work was carried out in conjunction with re-profiling works (described in Section 10), to limit the impact of the in-channel works on flood capacity and levels.

The sections which were surveyed on the site visit, with their associated roughness zones, are shown in Figures 5b and 5d. Figures 5a and 5c show the same sections before the restoration. It must be stressed that these 'before' sections were not measured but estimated from approximated data given by the designer.

A comparison of the pre and post cross sections show that the channel was wider, with a steeper bank slope and the bank edge dropping straight down into the channel. After the works both sections have a shallow slope angle and a berm narrowing the channel.

The resulting impact on flows of this restoration can be demonstrated in the CES by comparing the stage discharge plots of the cross-sections in both pre and post conditions. Figure 5e shows the comparison.

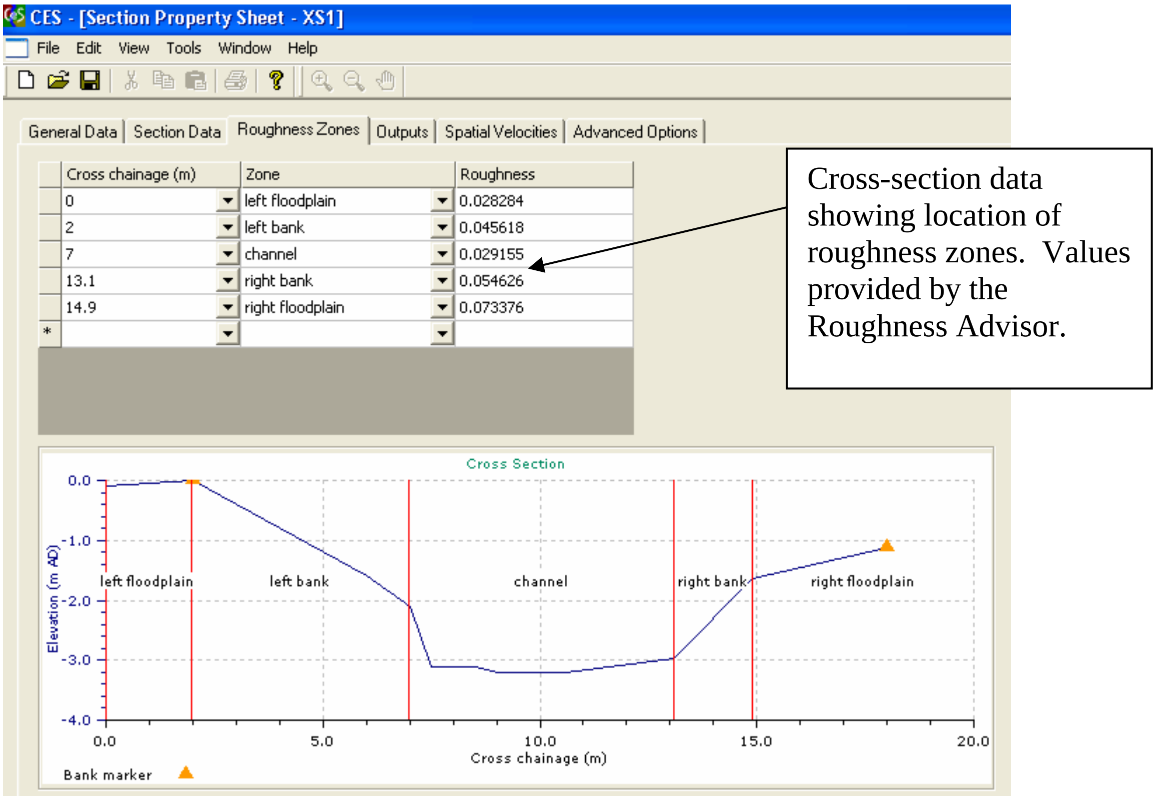


Figure 5a. Rhee cross section 1, pre works.

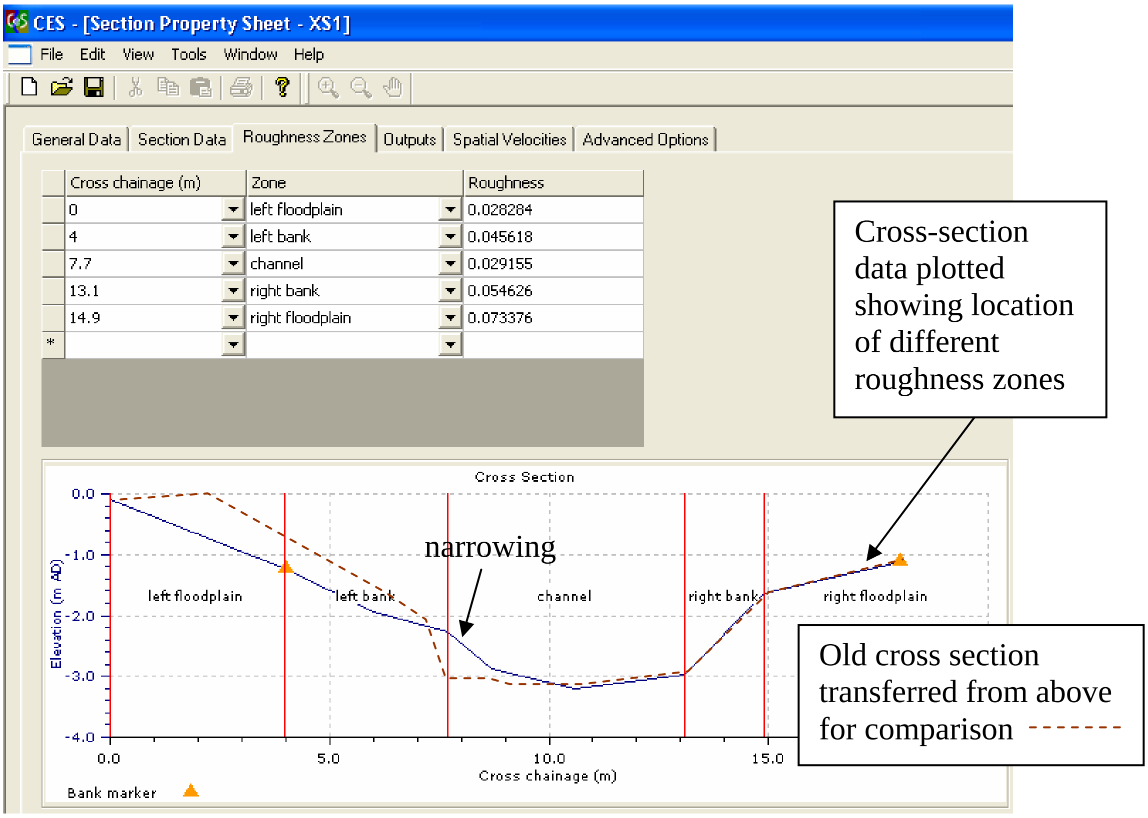


Figure 5b. Rhee cross section 1, post works showing narrowing.

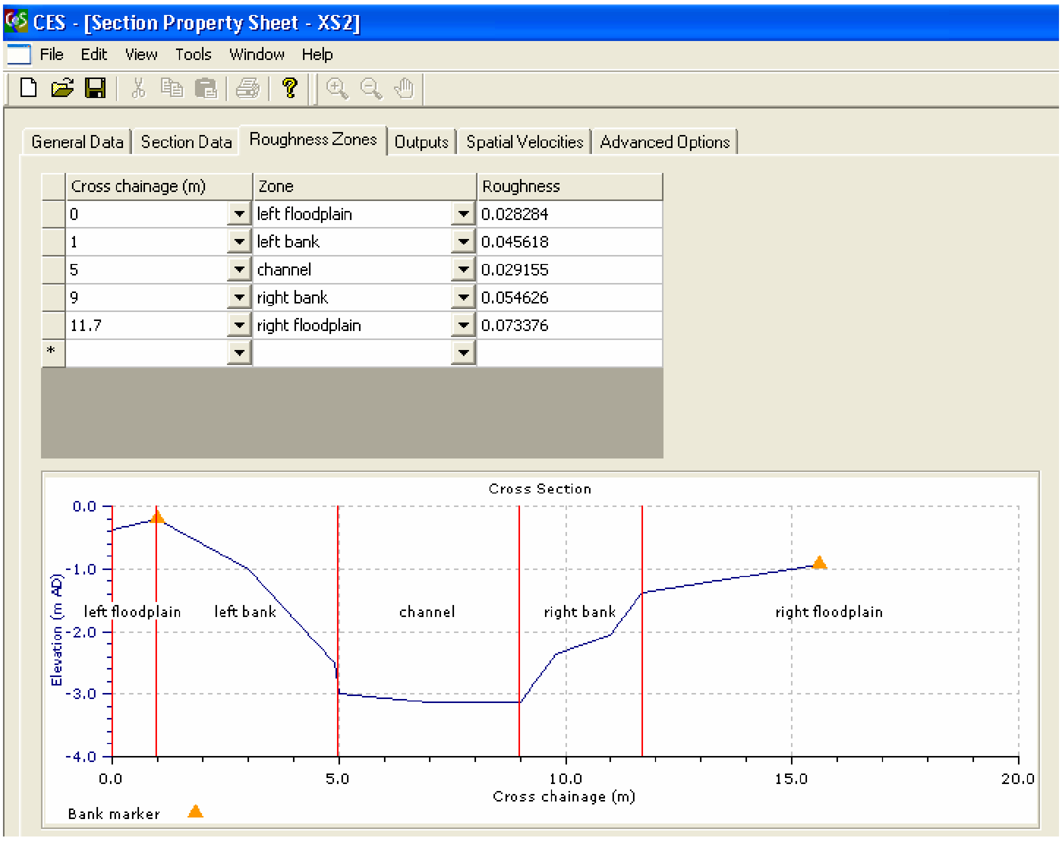


Figure 5c. Rhee cross section 2, pre works.

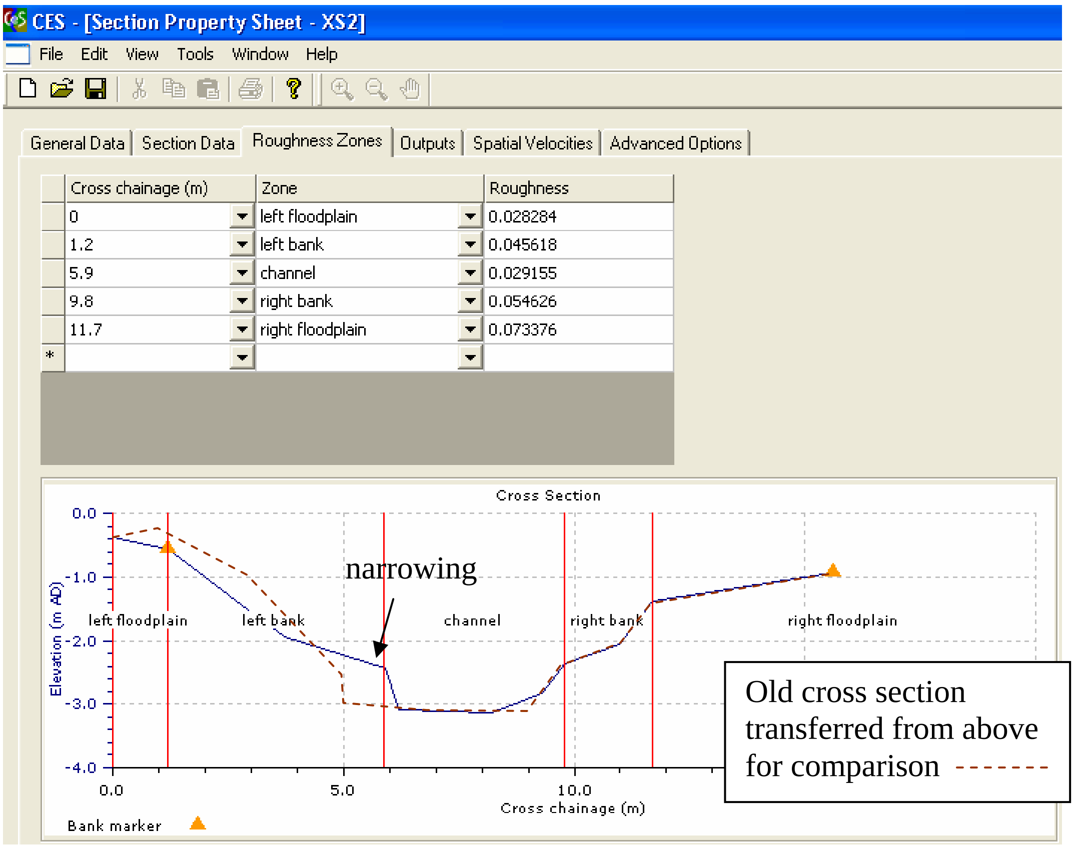


Figure 5d. Rhee cross section 2, post works showing narrowing.

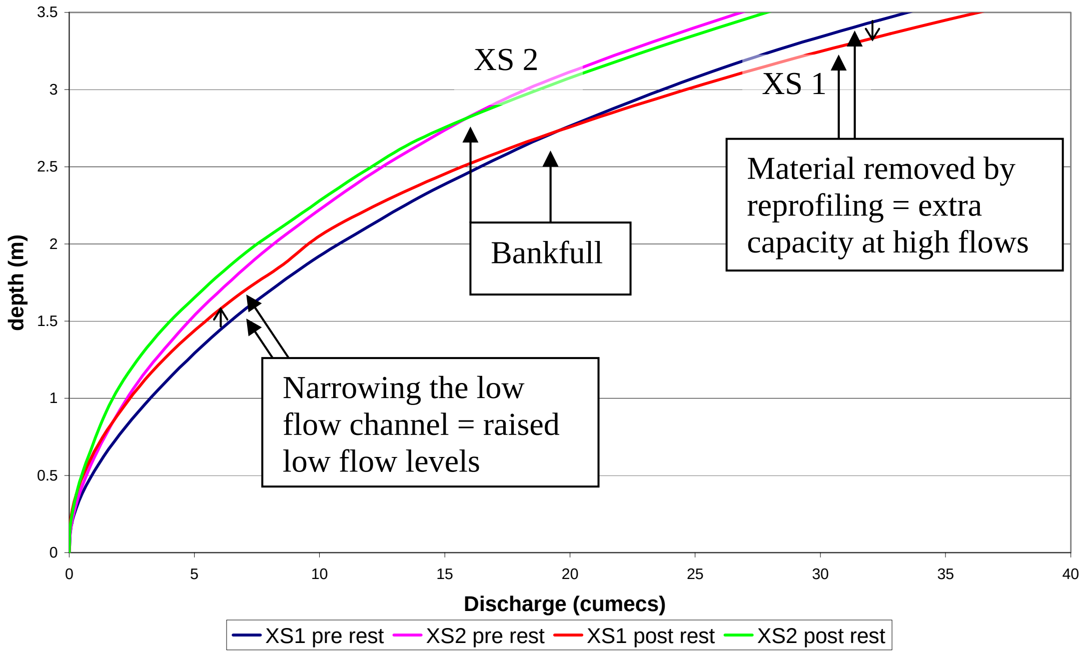


Figure 5e. Stage discharge curve for the River Rhee.

Figure 5e shows that up to the bankful level, the post restoration channel has a greater depth for the same discharge which is to be expected as the section is being narrowed.

As the water level approaches bankful level this changes and the post restoration depth is lower, at both sections, for the same discharge. This is due to the increased capacity of the channel where the bank has been reprofiled.

In this situation the modelling in CES is very useful to reassure that in a bankful flow situation the levels would be reduced but at low flows the levels have been raised by around 0.1m. These figures for the River Rhee demonstrate that the CES can be used to look at changes in cross-section shape, roughness variability and see the impact that those changes will have on water level, flow, velocity at individual sections and along a reach.

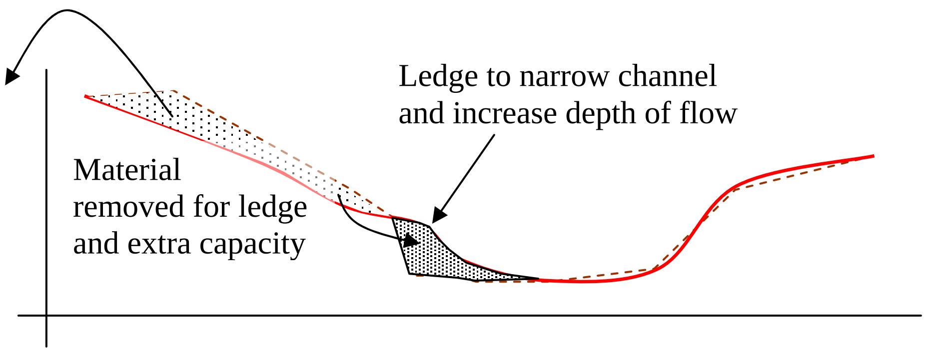


Figure 5f. Diagram of the changes to the cross section.

6 Riffles/gravel bed

Many rivers have been historically dredged to improve flood capacity and drainage. Ongoing maintenance works have also removed material from the river bed. In some systems in Eastern England rivers the natural bed material would be gravel or part gravel.

In such river systems, removal of the bed material will change the character of the river and have implications for its habitat value and resident species communities (fish, invertebrates, macrophytes, etc).

Where the river is known to have had a gravel bed, riffles or to have supported linked species (salmon, trout, etc), it is reasonable to explore the possibility of reintroducing/ replacing the missing bed material.

Reintroduction of gravel is generally proposed for two linked but essentially separate objectives;

1. Restoring/recreating riffle and pool sequences in a shallow, good gradient river;
2. Reducing the depth of the river bed (often dredged and over-deepened channels).

The 2nd objective is often less concerned with the pre-disturbance bed material and river features, but more a means to achieve the end result of a shallower river. The material used is gravel as it is potentially a less intrusive method and less prone to downstream impact than, say, rubble, clay or topsoil.

Sometimes the line between what is stated as 'riffle creation' and what is probably more bed raising becomes blurred. Without strict reference to a common terminology (e.g. RHS), this is likely to continue.

1. Restoring riffle and pool sequences.
Where these features have been lost, the common approach is to import a quantity of gravel and build a riffle. Riffles are defined in the RHS as;

> *"Shallow, fast-flowing water with a **distinctly disturbed** surface. Unbroken standing waves dominant."*

However, adherence to a strict definition is not often the reason for the feature. Invertebrates will hatch and fish will spawn on gravel beds that are not strictly riffles. So, ***'riffle'*** creation is often restoring/recreating shallow fast-flowing, habitat for the species that require them to complete their life cycle.

Examples of riffle creation

MOT - River Skerne (stone riffle)
ARM2 - Mink Creek, Canada (Riffles)
RRTH - Riffles

The concern with Eastern England rivers is often the lack of gradient. Installing a number of riffles in a given reach where the gradient is insufficient could result in the 'drowning out' of the upstream riffles. If inappropriately located, the gravel may just be washed away downstream.

In some cases the movement of material downstream is of major concern (e.g. near culverts or bridges) and the riffle may be designed to be 'fixed' in place. This usually involves the use of larger stone material less likely to be dislodged in high flows. These fixed structures are sometimes referred to as ***cobble riffles, cascades or rock weirs***, but generally protrude above the bed much further than a true riffle. They are also used to impound water levels and can thus have a proportionally larger backwater effect.

2. Bed raising.
Commonly low gradient rivers, such as those in the East of England, have been over-deepened. This can result in one of two scenarios:

1. The bed **and** water level are lowered;
2. Only the bed is lowered, the water level being retained higher by downstream influences.

Recently, works have been undertaken to attempt to reverse over-deepening and to actively raise the river bed back to its original profile. In some cases the bed has been raised by simply washing the old dredgings found on the river bank and placing them back into the river. However, it is normally not this simple. Bed raising is a costly exercise as it involves importing clean material in large volumes (gravel, or a bulk fill material (chalk, blockstone) capped with gravel), or attempting new ways of bulk fill prior to being 'capped' by a more natural substrate (hay bales covered with river gravel).

Examples of bed raising

MOT - River Chess (introducing gravels)
MOT - River Ogwen/Nant Francon (restoring over deepened)
MOT - Upper Kennet (raising bed levels)

If raising both bed and water level e.g Upper Kennet example, there is generally a need for a continuous gravel reach. If simply aiming to bring the bed up towards a water surface level, retained by another structure downstream, the often greater material requirement, and cost, of this method tends to result in discrete placement of gravel fill (on the basis of a pseudo riffle-pool (high bed/low bed) sequence). Done in the appropriate location, both can have great benefits for gravel spawning fish and invertebrates and general habitat enhancement.

Bed raising often results in a *run*, defined by the RHS as;

"Generally fast-moving water with rippled surface but no other major features of turbulence. Often associated with a high-velocity feature (e.g. rapid or riffle) just upstream or where the channel narrows and therefore speeds up the flow. Also, where relatively narrow channel has a moderate, even gradient."

6.1 Implications for flood levels and flood regime.

Riffle introduction and gravel bed raising both impact the channel by increasing the bed level, however this will often have no or little overall impact on flood flows and the bankful capacity of the river. This is dependent on the amount and extent of the bed raising or height of the riffle.

RIFFLES

With riffles, the placed gravels may increase the roughness of the channel locally. If this is over relatively short lengths of river (<20m) then the increase in roughness is unlikely to cause more than a few mm difference in water levels at low flows and the impact is likely to be “lost” at higher flood flows. The risk due to roughness is therefore low.

However, the riffle crest will also raise the bed, and may have an impact on the water levels locally and upstream, depending on the new level of the crest relative to the bed, top of bank, and the river gradient. Although the riffle may be drowned out at higher flows, the water levels will almost certainly be higher at low flows. Risk therefore increases with the relative height of the riffle crest.

The impacts of **riffles** are:

- Increased water levels at low flows due to raised crest level and increased bed roughness locally;
- Very small impact at higher flows if riffle heights are small in comparison with the bank height, and drown out at moderate to high flows.

Thus, riffles need to be designed as low level features which provide flow diversity at low flows and drown out at higher flows.

Rock weirs/cobble weirs and rock cascades are generally much higher above the bed surface than the riffles and create more of an increase in water levels. The tables below show the relative risks and impacts of riffles and rock weirs/cobble weirs and rock cascades.

GRAVEL BED

Introduction of a gravel bed will increase roughness (if this is not already the dominant bed material), having a small impact on water levels. The new gravel bed is usually designed to replicate a previous bed level (either from historic measurements, template adjacent reaches or geomorphological calculations). The impact will be different for cases where bed *and* water levels are to be raised, and for those where the bed is raised to an original level, say prior to dredging. In this latter case, the original pre-dredged bed may be obvious from an old bed profile, drawings and plans pre-dredging works or from structures and bridges. The input of a geomorphologist is useful to help in determining the original bed profile.

The impacts of bed raising are:

- Very small increase in roughness through introduction of gravel into deep sluggish reaches, which are ***below*** the original bed profile ;
- Increased roughness and water levels if gravel placed into deep sluggish reaches which are raised ***above*** the original bed profile;
- Increase in roughness and water levels if gravel introduced to raise ***bed levels,*** to original bed levels therefore increasing ***water levels*** . Impact dependant upon remaining channel capacity.

6.2 Impacts and risks

Types of techniques:	**Risk of increased flood levels**			**Impacts**
	High	**Med**	**Low**	
Riffles			✓	Potential to affect conveyance and roughness. Riffles should only raise low flow levels by <10cm, or crest height less than 20% relative to bank height. Should be drowned out by moderate to high flows.
Cobble riffles/Rock weirs/Cascades	✓	✓		Greater potential to affect conveyance and roughness. Structures that raise low flow levels by >20cm, or crest height greater than 20% relative to bank height
Gravel bed I [Infilling] (fills deep water channel up to original bed level)			✓	Applies where channel is over-deep relative to downstream depths and infilling seeks to increase velocity/reduce deep silty pools. Where gravel is not currently the dominant bed type.
Gravel bed II [Raise Bed & Water levels] Raises bed above original bed level and raises water levels		✓		Bed level raised above the original bed level therefore increasing water levels. Where gravel is not currently the dominant bed type.

6.3 The need and requirements for modelling

RIFFLES

Types of techniques:	None required	Hand calcs	CES	ISIS/INFO WORKS	Comments
Riffles	✓	✓	✓		For riffles (a low crest relative to the bank height) then either no modelling or perhaps a hand calculation based on a crump weir can be done to check levels upstream and backwater extent. For other features with a higher crest use CES or 1D models.
Cobble riffles/ Rock weirs/ Cascades			✓	✓	

Crest height
When considering whether modelling of a riffle is required, the relationship between the riffle crest and the water surface is the key factor. If the riffle crest is thought to be significant relative to the channel depth, then modelling using the CES should be undertaken.

For example a riffle of crest height 0.1m in a 0.7 m deep channel will cause a rise in water levels locally and upstream but may be drowned out in higher flows. Each situation with riffles is individual and it is difficult to give “rules of thumb”. However the rise in water levels upstream at low flows will be at least the same as the height of the riffle crest. So a riffle crest of 0.1m will raise the water level upstream by at least the same amount of 0.1m. But if the water level downstream of the riffle rises more than the 0.1m crest, the riffle will be drowned out. Flows with water levels exceeding this would be unaffected by the new riffle.

Backwater impact
The riffle will cause a rise in water levels upstream which hydraulically is called a backwater. The length of the backwater impact upstream can be calculated using the formula:

$$0.7 * \frac{depth}{slope}$$

So for a channel with a slope of 0.001 (1 in 1000) and a low flow depth raised from 0.5m to 0.8m by a riffle of 0.3m height the length of the backwater influence upstream would be 560m as calculated below.

$$0.7 * \frac{0.8m}{0.001} = 560m$$

If a fixed structure such as a rock weir or cascade is planned, it is advisable that it is modelled using the CES as it may not be drowned out by medium to high flows. The structure can be modelled as a change in section. Its impact over the reach of river, especially upstream, should be investigated. This will require more sections.

Data needed 🖫🖫(🖫)🖫🖫

Cross-section topography (before the riffle and after the riffle);
a comparison of the stage discharge relationship of the two sections.

For reach scale investigation with CES, an additional section will be needed a few hundred metres upstream.

Resources £ £ (£) £ £

The time taken to collect the data for cross-sections on a reach over a few hundred metres would be 1 day and then 1 day for analysis using the CES.

There is no capacity for modelling structures in the CES software, but this type of bed raising can be modelled using a series of sections at different levels in the CES software with the backwater function. As an alternative a riffle could also be modelled as a structure using the other 1D models available (ISIS, INFOWORKS, HEC-RAS). This is relatively straightforward to undertake, requires cross-sections and slopes and discharge data, as for CES but also a level at the downstream end of the model, whereas CES calculates the normal depth at the downstream end. The data collection for these other 1D models would be the same as for CES model. It would be more time consuming and costly to use these models, than using CES, for this relatively simple calculation. The use of these other models should be considered for a more substantial structure with a high crest level or if the impact of unsteady flow conditions was required.

GRAVEL BED

Types of techniques:	None required	Hand calcs	CES	ISIS/INFO WORKS	Comments
Gravel bed I [Infilling] (fills deep water channel up to original bed level)	✓		✓		No modelling required for gravel put in locally, below or up to the original bed profile.
Gravel bed II [Raise Bed & Water levels] Raises bed above original bed level and raises water levels			✓		With gravel on a more extensive basis use roughness advisor in CES to look at water level rise.

For the introduction of gravel to increase the bed level up towards the original bed level, modelling using CES may not be needed especially if the reach to be infilled is deep and sluggish. Modelling using CES is recommended if the gravel bed will raise the water surface, and where gravel was not previously the bed material. CES should be used if a significant length of bed plus water surface is to be raised especially if the bed level rise is above the original bed level. This should be a relatively straightforward procedure needing a representative cross-section and slope (approximately 0.5 day measuring in the field) and 0.5 day analysis.

Data needed

Representative cross-section;
Slope.

Resources £ £ £ £ £

The time taken to collect the data for cross-sections on a reach over a few hundred metres would be 0.5 days and then 0.5 days for analysis using the CES.

Modelling using the CES can also investigate the backwater profile upstream and its potential impact. This can be seen in the example on the River Welland in Section 9. The advantage of this type of modelling of bed raising is that the backwater profile at a range of flows can be investigated, different options in terms of the design (bed height and length) can be compared, and the velocities over the riffle can be determined.

Another possible rehabilitation mechanism lies somewhere between constructing a riffle and introducing a gravel bed. This could be a ‘loose structure’ where gravel is introduced into the bed (see section 3.9, MOT), and allowed to settle into a pool/riffle sequence. This type of feature does not necessarily have a fixed crest which can be modelled so it would be better to be modelled by the CES software with a change in bed roughness which would highlight the change in water levels due to the change in roughness characteristics. Again the resource requirements for investigating this change in roughness is as above and would give the comparison in water levels for the different roughness at the same section.

6.4 Case study; the River Waveney at Homersfield

At this site several new features were planned as part of river rehabilitation works. This example shows well how the CES can be used to check the water level rise due to the introduction of gravel. The plan is to enhance the bridge riffle and to put in place additional 'riffles' downstream. As the downstream section is deep and low gradient, these further features are in fact likely to be local bed raising back to a pre-dredged, original bed profile. This case study looks at the effect of raising the bed to see what impact it has up and downstream.

Cross section 2, riffle just downstream of the bridge.

The proposal is to enhance the riffle in the photo (cross section 2, XS2), so it is important to know if any of the downstream works will drown out the feature.

Further downstream, cross section 1 (XS1) is in a lower gradient deeper reach. Here the emphasis will be on raising the bed to provide fish spawning habitat. The gravel fill section (XS1) is planned to have a 'crest' of 0.45m above present bed level which is approximately 1/5th of the depth of the channel. It is likely that this will have some influence on levels upstream and some influence locally on water levels.

These assumptions can be checked using the CES for the pre restoration conditions and changing the level of XS1 which is the section were the changes are to occur. Figure 6a shows the pre-restoration conditions and Figure 6b shows it raised by 0.45m.

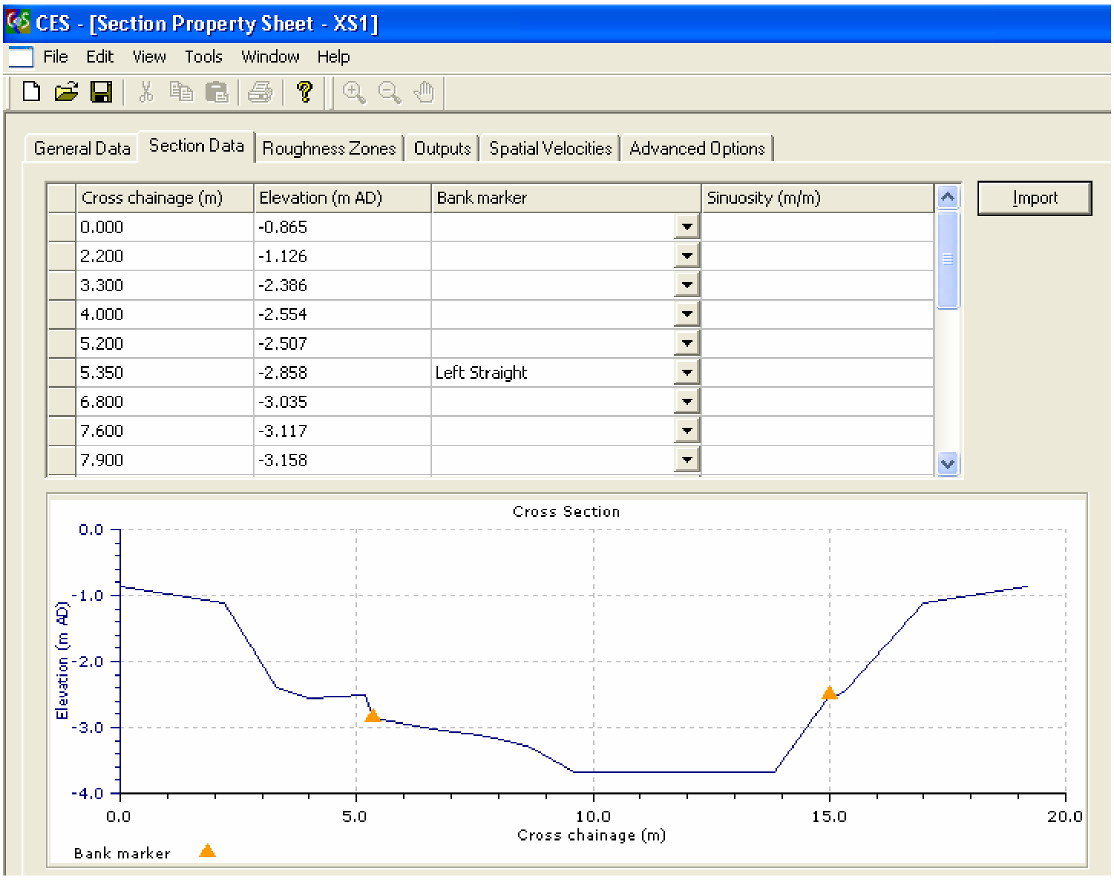


Figure 6a. Waveney at Homersfield, XS1, 2004 pre-works conditions.

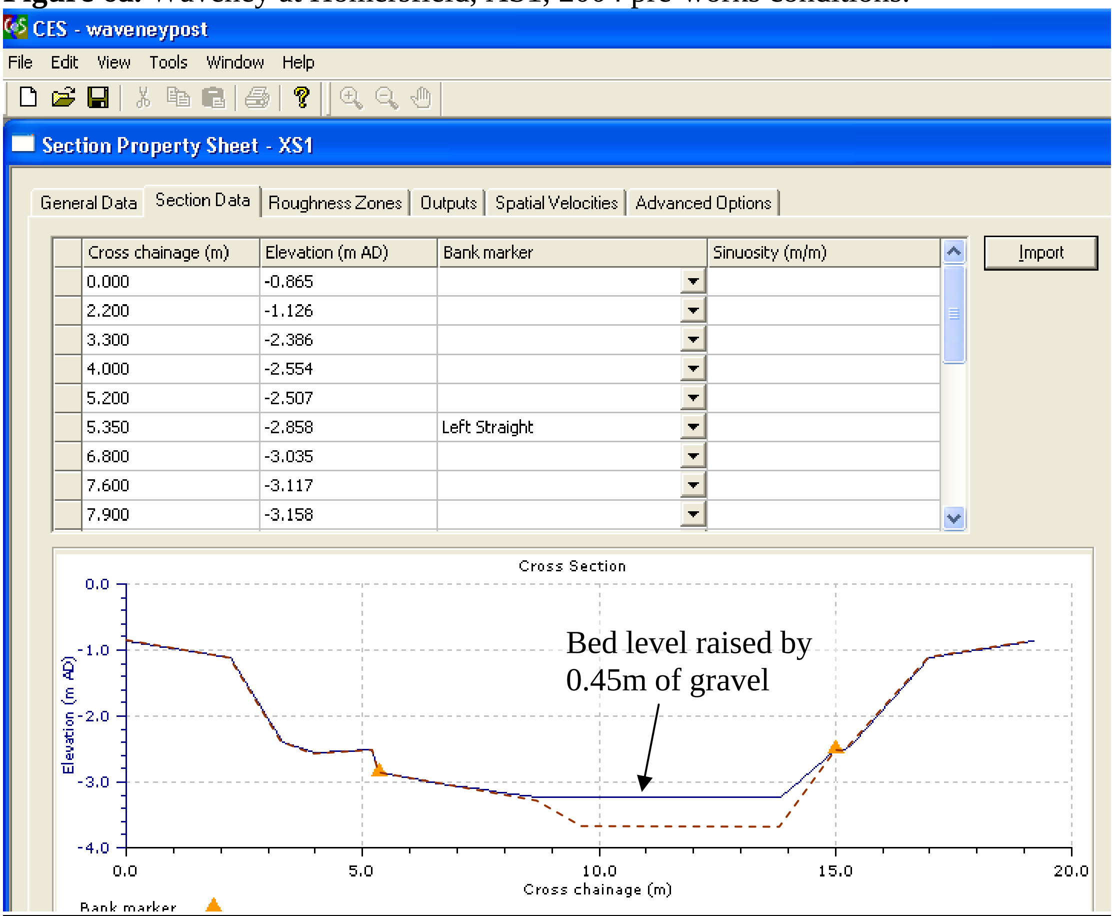


Figure 6b. Waveney at Homersfield, XS1, predicted conditions with gravel import.

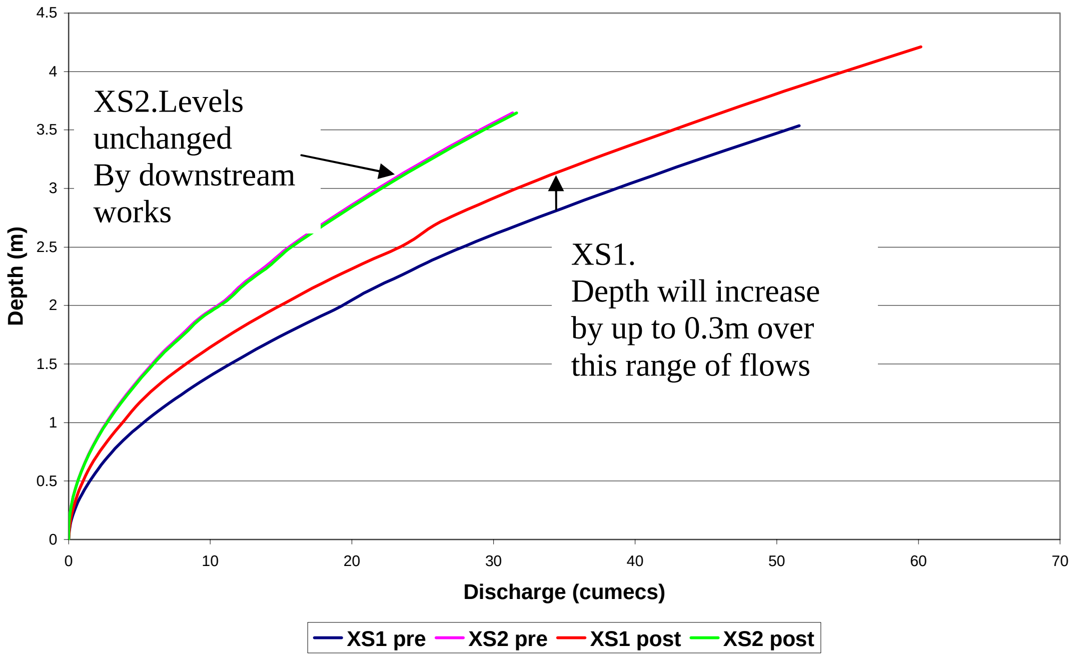


Figure 6c. Waveney stage discharge relationship.

In Figure 6c the stage discharge relationship shows that at section 1 the water depths are consistently higher by approximately 0.2 to 0.3m, but at section 2, 185m upstream of section 1, the relationship is unchanged.

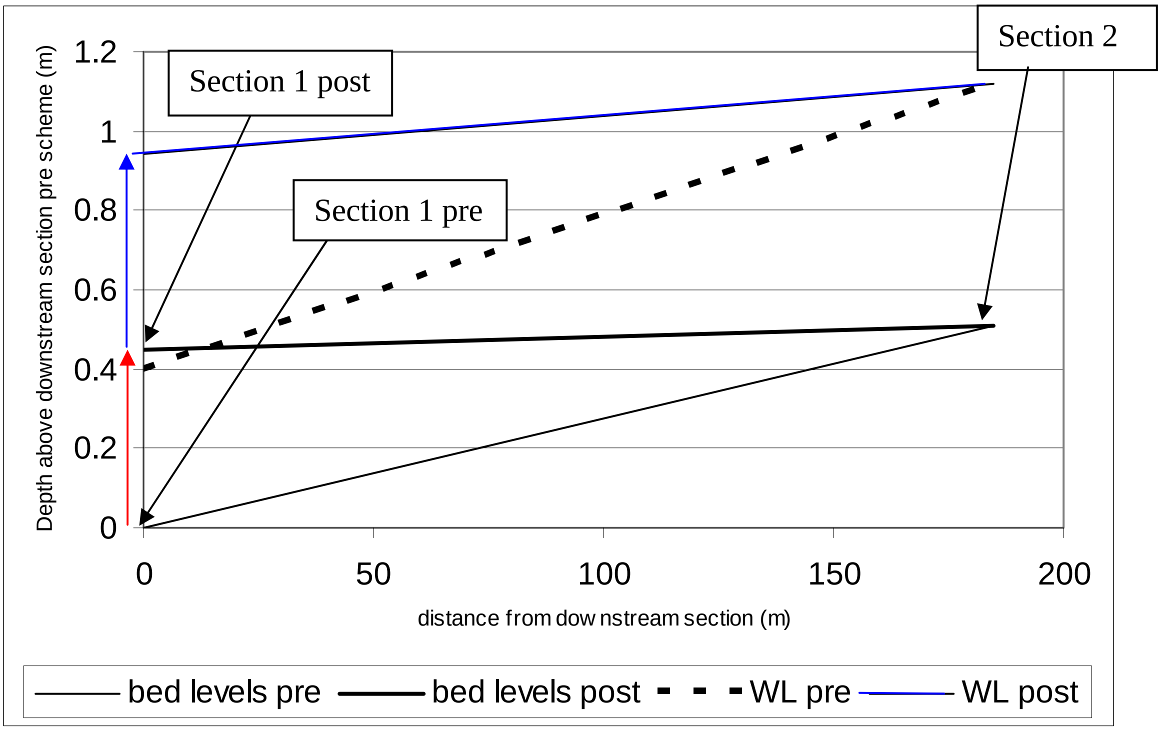


Figure 6d. Backwater influence of the gravel

Figure 6d shows the impact that the increase in bed level (caused by the added gravel) has on water levels. The plots of bed and water levels show that the riffle has increased the bed level at section 1 by 0.45m (red arrow). The corresponding rise in water level (using a flow of 1 cumec) is 0.5m. The water level rises a little more than the bed level as the gravel surface is rougher than the bare bed surface. At section 2 the corresponding water level rise is negligible. This shows that the backwater effect due to the bed being raised has little or no impact on the water levels at the section upstream. The section raised was over deep and infilling with gravel back to a pre-dredged bed level does not have a large impact upstream.

This example shows how CES, and the backwater calculation included in the CES, can be used to confirm that the impact of features (riffles or bed raising) can have some impact locally, but any immediate rise may be lost further upstream. In this situation the backwater impact of a rise of 50cm in water level at the riffle was not noticeable at the section 185m upstream. Gradient is the key determining factor of how quickly the effect is lost.

6.5 Case study; the River Wensum at Bintree

On the River Wensum at Bintree restoration has included bed raising, glides, narrowing, point bars and fencing. Again there were no pre-restoration sections for comparison and the water was deep on the day of the site visit so it was difficult to measure cross-sections except at the raised sections. The pre and post sections show the new bed and what may have been a typical section before the gravel was placed.

Cross section 1

Top left.
Shortly after works completed, new raised gravel bed.

Top right.
Summer macrophytes growth in the same year. Gravel is 300m below the surface.

Left.
2005. The vegetation has encroached into the now shallow channel, resulting in a more sinuous course, and greater velocity.

Cross section 2

Top left.
Gravel recently placed to shallow the river u/s of cattle drink (flow is towards the camera).

Top right.
Same view in summer that year. Limited impact at low flows due to low gradient.

Left.
Opposite view from gravel bed to cattle drink. The flow velocity has scoured the bed free of silt and provided spawning habitat. (Inset: spawning redd)

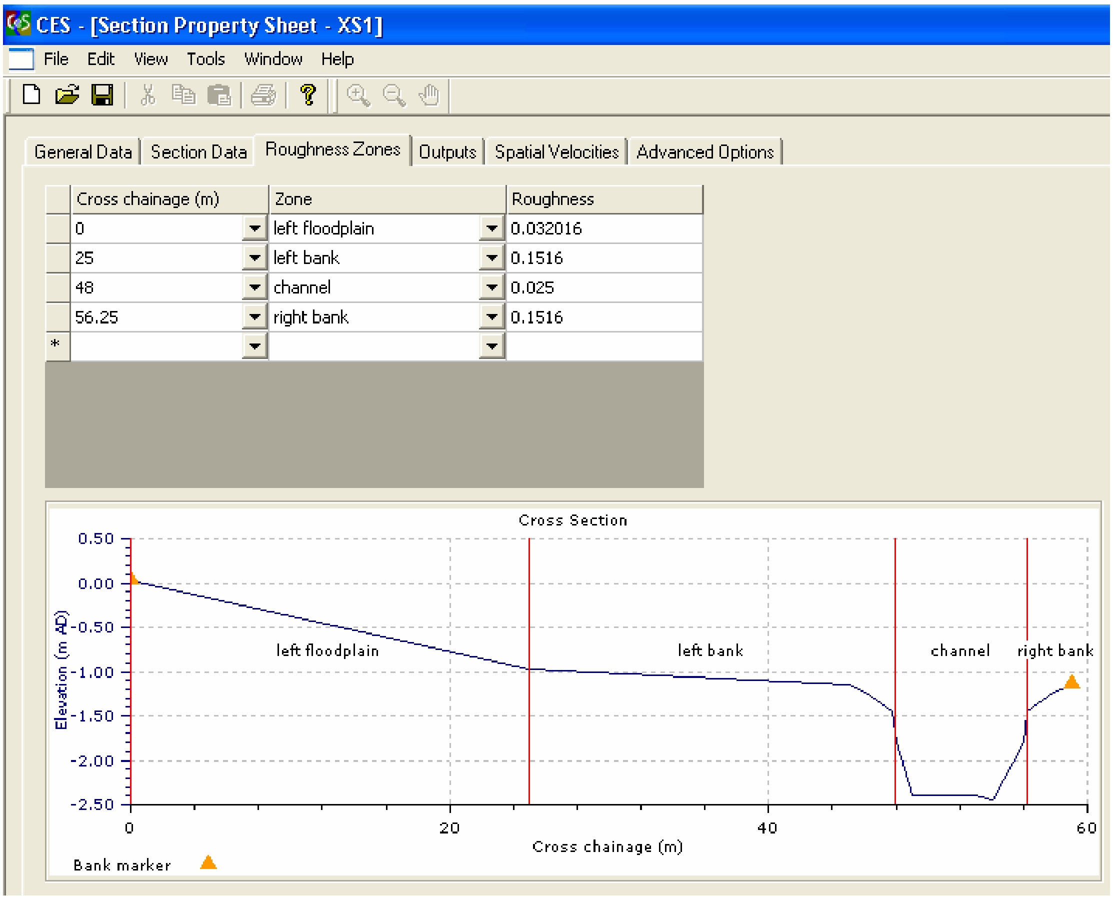


Figure 6e. River Wensum at Bintree. Pre restoration.

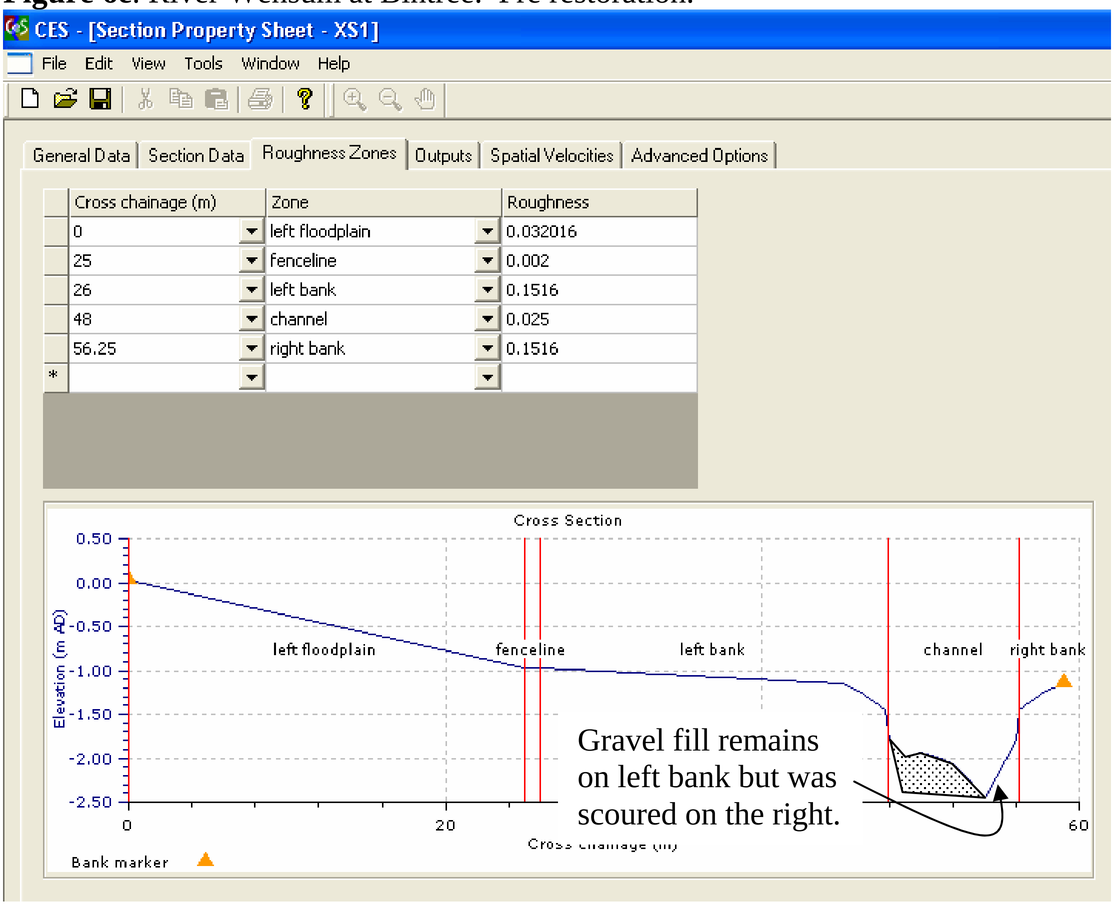


Figure 6f. River Wensum at Bintree. Post restoration cross section.

Figure 6e shows the section as it was without the gravel and the fenceline. Figure 6f shows the same section with the new raised bed and fenceline. The material has undergone some movement and a deeper section has been eroded through the gravel. This coincides with the photographic evidence of marginal vegetation encroaching onto the gravel. As the vegetation has grown out from the left bank it has created a more sinuous channel, resulting in the right bank flow now taking on the characteristics of a bend. Here the secondary currents are eroding the gravel creating a deeper 'pool' feature.

Figure 6g shows the comparison of the stage discharge relationships at the two sections.

When the stage discharge graphs for these two sections (XS1) are compared, the stage is higher at this section for the post restoration condition, until at higher flows when the change is negligible, showing that the feature is drowned out and is having little effect in flood conditions.

Looking at another section further downstream (XS2), the pre and post restoration stage-discharge curves were compared and showed that the stage is higher at low flows (due to the gravel) but for peak flows the stage is lower in the post restoration condition.

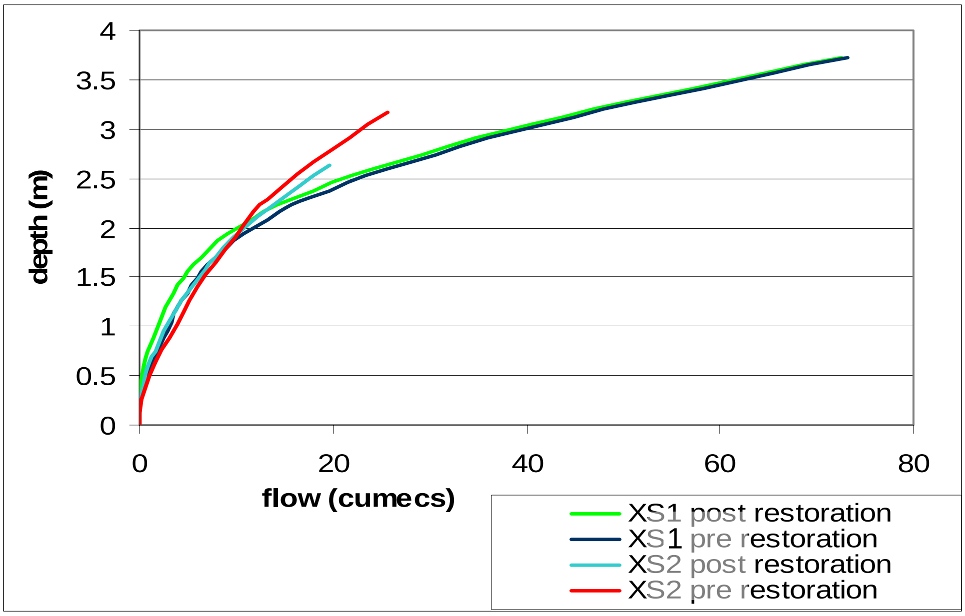


Figure 6g. Stage discharge relationship for the Wensum at Bintree

The example on the Wensum demonstrates the useful nature of the CES in looking at the effects of bed raising through simply modelling the changes in cross-section and any roughness changes. The effects can be seen in raising the water levels at lower flows but are often seen as being negligible at higher flows. At different cross-sections the effects can also be different, as can be seen on the two cross-section measured. This shows that it is difficult to generalise and a simple model such as the CES can be a great benefit in demonstrating the differences along a reach.

Measures such as inclusion of fencing can be modelled successfully using the changes in roughness from the roughness advisor within the CES (see Section 13).

7 Backwaters

In heavily managed river systems areas of slow or still water connected to the main channel are rare. They were often seen as places to dispose of dredgings and excess spoil from earthworks. In addition, older backwaters tend to silt up and colonise with vegetation. Through succession they become dry land; often low places that flood frequently.

The disappearance of backwaters has reduced the refuge areas for fish and invertebrates in times of flood; where they could have avoided being washed downstream by fast velocities. In addition, fish fry often use backwaters to hide in the shallow warmer water. As they are a transition between the running waters of stream and the still water of a pond, they also add to the diversity of habitat available in a reach.

Backwaters can be the main objective (ORSU construction – Off-River Support/Supplementary Unit) or they may just be a useful by-product of other works. In the re-routing or re-meandering of old river courses, some remnants of the straight channel may become redundant from which a backwater can be created. This can help reduce costs by negating the need to import fill material.

Backwaters are often seen as a fisheries enhancement, because of the implicit benefits for fish. However, their benefit extends beyond this, and as such they should be designed with a variety of species in mind. A mosaic of water depths, bank slopes, margin substrates, etc should be designed in. A natural backwater is essentially a pond with a connection to the river, so a good reference is Williams et al (1999). This text explains and illustrates, with examples, the requirements of many species when considering a pond design.

Williams et al (1999) *The pond book, a guide to the management and creation of ponds*, Ponds Conservation Trust, Oxford.

http://www.brookes.ac.uk/other/oldpondaction_250102/thepondbook/contents_page.htm

Examples of backwater creation

MOT – River Skerne (Backwaters)
MOT – River Cole (Backwaters)

7.1 Implications for flood levels and flood regime.

Generally the area of water in a backwater does not have much impact on the flowing water and flood water levels. Usually the area of storage is in addition to the main channel and simply allows for a little extra storage of water. Although the extra storage is unlikely to be significant it is always a positive gain. In the majority of cases the flood water levels will not increase.

In general, backwaters have no effect, or rather a small reducing effect, on flooding. This assumes that the material that has been excavated to create the feature has not been left within the floodplain to cause an obstruction.

7.2 Impacts and risks

Types of techniques:	**Risk of increased flood levels**			**Impacts**
	High	**Med**	**Low**	
Backwaters				No impact, minimal risk

7.3 The need and requirements for modelling

Types of techniques:	**None required**	**Hand calcs**	**CES**	**ISIS/INFO WORKS**	**Comments**
Backwaters	✓				No modelling required

Modelling is rarely required unless part of a suite of other techniques.

Data needed n/a

Resources n/a

7.4 Case study; the River Rhee at Wendy

In addition to the narrowing and reprofiling works undertaken at this site, a backwater habitat was designed to provide refuge to fish and invertebrates in floods and to increase the diversity of habitat (slow/still water as well as the flowing river course).

The backwater involved excavating 775 m^3 of spoil to create a pond connected to the river by a in/outflow. The material was used to form a linear ridge/beetle bank. It was the intention of the landowner to then plant this as a small copse for bird cover. The ridge was aligned to follow the direction of flood flows, and was broken in place to allow flood water flow around the 0.8m high feature.

The location of the backwater was known to flood regularly. The feature does not interfere with the flow of the channel. At bankful flows it fills up to the bank top, providing extra capacity (very little in terms of its contribution to alleviating floods, but enough to confirm that it **does not** increase the flood risk).

Backwater in 2002, shallow slopes with little growth, and again in late 2003 with marginal growth establishing. The connection with the river is at the far end of the photos.

Backwater after construction in 2001, showing connection to river and line of spoil/beetle bank, to the left of the photo. Similar view in 2004, now well vegetated.

8 Reconnecting remnant meanders

River rehabilitation looks to restore the form and function of the river as far as is possible within the constraints that exist. In a location where the past course and dimensions of the river have been lost or blurred by centuries of management, it is a difficult and costly process of background information searches and complex design decisions.

In some instances, however, the old channel may still remain intact, or partially intact. This offers greater potential to restore the channel with significantly less design costs. The principle being to excavate the old course to the old depth and width and use this as the 'natural' cross section and channel capacity. The main features of the design are:

- remnant meander is at a higher level than the canalised channel;
- more features such as pools, riffles, bends and vegetation are established in the meander;
- the remnant meander channel is reconnected with the floodplain and the floodplain area is inundated more frequently possibly becoming a wetland area; and
- the canalised section sometimes remains with a sweetening flow or is blocked off and either filled in or remains as a backwater.

Examples of reconnecting meanders

MOT – Reconnecting remnant meanders (Little Ouse)

8.1 Implications for flood levels and flood regime.

Though restoring the original channel profile and gradient will meet the objectives of restoring the river, it also may impact on the flood risk management objectives for the river. If the by-passing cut was oversized and the overall length shortened (gradient increased) this will have resulted in increased flood capacity and conveyance. Reversing this process by restoring the old smaller and longer course may reduce the capacity and increase roughness below the level necessary to meet flood risk management standards resulting in increased flooding.

Such a project must always consider the implications of increased floodplain wetting and out of bank events.

8.2 Impacts and risks

Types of techniques:	**Risk of increased flood levels**			**Impacts**
	High	**Med**	**Low**	
Reconnecting remnant meanders	✓			Re-routing the flow will have consequences for water levels and flood inundation. Modelling should be an integral element of this type of work unless sound justification is provided.

8.3 The need and requirements for modelling

Types of techniques:	None required	Hand calcs	CES	ISIS/INFO WORKS	Comments
Reconnecting remnant meanders			✓	✓	Generally an unsteady state model required as objective of restoration is to get water back onto floodplain where water will be stored.

From the point of Flood Risk Management and Development Control, with the frequency of inundation being greater and the flow carrying capacity of the channel decreasing it is probable that modelling would be required unless clear reasons can be given to refute this. If all parties have agreed that the objective of the project is to increase water levels and floodplain inundation, and there is no impact on people, property and infrastructure then modelling may not be required. However the impact on flows and levels both upstream and downstream would also need to be investigated.

This type of project is going to be a more costly venture than a few deflectors. It will require detailed design and as part of this the modelling can have a beneficial effect in helping to establish scientifically valid design parameters for the remnant meander, giving water levels, flow velocities and an indication of frequency of flooding. It will also help ensure that the balance between increasing inundation of the floodplain, raising low water levels and providing a different floodplain flooding regime does not cause greater flood water levels. Though this has cost implications to the alternative approach of getting in there with a digger and having a go, it is a far better approach to illustrating the benefits of river rehabilitation in a structured way. More complex works should have a greater degree of design and appraisal built into the budget as standard.

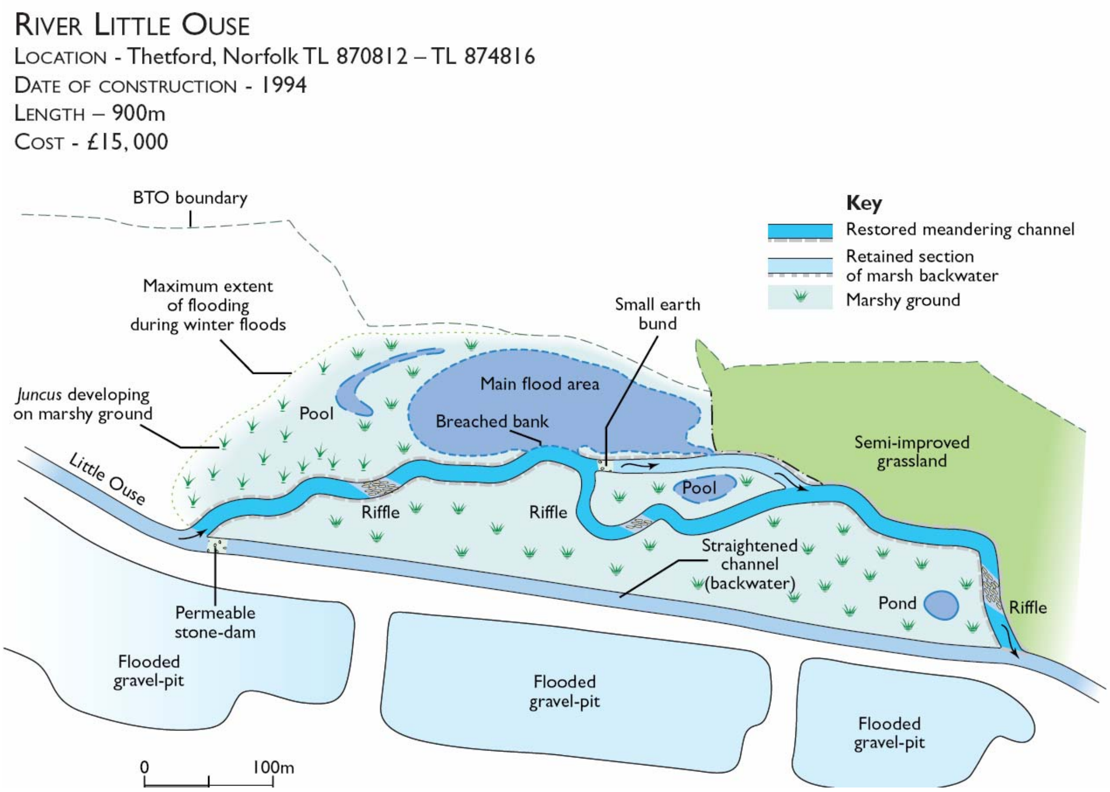
As the CES only deals with single channels and reconnecting a meander involves a looped system then modelling of the channel would be suggested using the standard 1D models. The system could be modelled using a variety of single flows – a steady state – where the flow does not vary with time, or using a hydrograph – unsteady state – where a flow event is considered over a period of a few hours or days. A steady state is fine to use when looking at in-channel flows where all the water goes down the channel. When the water spills out onto the floodplain water is stored and an unsteady state model should be used to get a true picture of the conditions in a flood event. This flood event would either be a real event or a statistical event (e.g 1 in 100 year) which can be predicted from a method such as the Flood Estimation Handbook using catchment characteristics, rainfall and flow records from the catchment.

Data needed
Cross-section topography along the new and old courses;
Floodplain mapping for flood volumes;
Flow gauge data.

Resources £ £ £ £ £
This type of work would be undertaken as part of the design process. If using an unsteady state model, the hydraulic analysis might be between £5K and £20K.

Case Study; the Little Ouse

The Little Ouse at Thetford is a looped system.



From the existing channel a new channel was created which reconnected the old meanders and created a marshy area of ground on the floodplain. There was a retained section of marshy backwater between parts of the old meander. This meant that hydraulically the system is complex with flow being split, and then rejoining the channel.

Newly opened meandering channel

This type of system cannot be modelled using the CES software as this is for a single thread channel in a steady state condition. If the Little Ouse system was to be modelled it would require an unsteady 1D model such as ISIS or INFOWORKS or a 2D/3D model depending on the reason for the modelling.

1D Modelling

The 1D models would show the water levels and flows at a range of flow conditions over a flood event, either one that had happened or a simulated statistical event, say 1 in 100 yr. The 1D model would show the split of flows, the flooded outline, depths and extent of water on floodplain and the velocities along and over the banks.

A 1D model would probably have been sufficient in the case of the Little Ouse project to demonstrate the flow splits, extents of flooding and flood levels.

2D and 3D Modelling

The 2D or 3D model would give all the information as above but on a more limited scale, but could show in greater detail the velocities and shear stresses not only across and along the channel but also through the water depth for any particular flow. It would show the flow more accurately around structures or trees and where erosion might take place. This accuracy would require more data on a grid along the channel and on the floodplain and would be more time consuming to set up and run.

8.4 Case Study; Shopham Loop of the River Rother (W. Sussex)

The River Rother had a narrow channel cut between the two ends of a meander loop in the late 18th century. The cut incorporated gates for barges to bypass the loop. As the structure fell into disrepair, the gates broke and the loop was permanently cut off from the main channel in the 1930's. The Sussex Agency team were keen to restore the channel as a functioning system.

The area between the loop and the canal cut is an area of grazing land. Part of the proposal was to lower the banks through the loop reach to allow flood water to pass more frequently out onto the flood plain, and to make this area of land wetter by creating areas of standing flood water. Hydraulic modelling was required to ensure that flood levels upstream of the loop were not increased when the old course was reinstated. The modelling provided indications of how frequently the water would pass onto the floodplain area between the loop and the cut. The Rother is a sand dominated system at this point and the hydraulic model provided vital information on the velocity profiles through the reach and across each section. These data were used in another model to investigate the extent of sand movement through the loop and where areas of sand would be likely to deposit, both in the loop and downstream. The hydraulic model was instrumental in designing the size and shape of the channel to ensure a design which fulfilled the objectives of the project.

A steady state 1D model, ISIS was used. The flows at bankful were compared in the pre and post restoration situations to check that the water would come out of the restored loop, onto the floodplain more frequently, and at a lower discharge than in the existing case. The steady state model was used to check the design and look at different options of cross-section shape and size. The model extended upstream to houses and checks were undertaken to ensure that the flood levels under the restoration scheme were no higher. The downstream end of the model was at a road bridge and the model was used to ensure that flood levels at the bridge were no higher than under existing conditions.

A 1D model was used in this situation rather than the simpler CES model because this was a looped system with two channels – the canal cut and the loop, which together cannot be modelled in the CES. A steady state model instead of an unsteady state model was used to keep the costs lower, and the storage of water on the floodplain was not an issue in this project.

The results from the project showed:

- the channel loop cross-section shapes and dimensions;
- the velocity profiles across and along the river;
- the discharge at which the water would come out of bank onto the floodplain and some indication of the likely frequency of that flow;
- the longitudinal section for the reach showing flood levels for pre and post project situations.

Aerial photo of Shopham Loop, post connection (Environment Agency).

9 Replacing weirs

The Doomsday Survey of 1086 documents 5624 weirs built for milling in southern England (Hogden 1939). The use of low weirs for abstraction purposes in agricultural catchments with their drained water tables, was also common in the last century. Many of these structures are now defunct, but still present in our watercourses. Similarly, weirs originally built for a variety of purposes can be found in many channels where their purpose has been lost or forgotten. Little thought was ever given to how or who would remove these structures and what effect they may have on the river, its geomorphology, hydrology and habitat (Downward and Skinner 2005).

Weirs can be problematic to fish and invertebrate species, unable to travel upstream either as part of migration or return after flood events. They interrupt the sediment transport system. Material builds up behind them and pools erode downstream (sometimes right under the weir foundations) due to the energy released. This step in energy (low gradient water surface behind – impounded, and high gradient fall over – free fall) breaks the gradient of the river and uses this entire head in one location. A previously riffle pool stream of 1 in 1000 gradient becomes an impounded channel with a silty bed behind the weir and a drop structure with deep pool downstream.

In very low gradient systems such as those found in the East, a half metre weir could result in a ponded reach of 1km in a 1 in 2000 slope river. These ponded reaches are characteristically slow, silty, nutrient rich (agricultural phosphate in the silt), prone to excessive in-channel plant growth and need regular expenditure on maintenance programmes.

For such a seemingly small structure, the effects and resulting issues can be long lived, cumulative and costly.

The simple answer is to identify the use of the structure and if none is apparent look to remove the obstruction and reverse the trend of degradation. This reversal should rapidly achieve:

- removal of an artificial structure from the riverine landscape;
- free passage for fish and invertebrates;
- return to a more natural gradient (with further re-working over time through higher flows and bed adjustment);
- reconnecting the sediment transport system (fine silts travel through the reach and deposit in natural eddies, gravel is scoured by high velocities, gravel movement (if applicable) encourages loose riffles for spawning and invertebrate colonisation;
- higher velocities and reduced silt deposition limit in-channel nuisance plant growth;
- erosive pressure downstream of the weir is reduced.

Bullet point 3, return of a more natural longitudinal river bed slope, rather than the ponded (long pool) – step – scour pool sequence, is very dependant on the sediment regime within the river system and the age of the structure. For instance in Scotland on the River N. Esk an old mill of 2m in height has a gravel/boulder bed up to its very crest due to the high degree of sediment movement in the system and age (100+ years) of the structure. Consequently, the new housing development immediately upstream is reliant upon the structural integrity of that weir to prevent its walled foundations being undercut as that wall is built on the 2m of deposited gravels.

In Eastern England rivers the sediment is more likely to be fine silts and clays, with limited gravels available in some rivers. However, the impact of sediment build up and regular dredging/weed maintenance is enough to alter the long profile of the watercourse. Simple removal of the entire structure may lead to instability within the reach and associated impacts up and downstream.

A solution is to consider removal of the structure and replacement with a lower, longer crest; a fixed riffle or cascade.

Examples of weir removals

MOT - Diversion of a river valley (Sugar Brook)
MOT - Bifurcation weir and sidespill (River Cole)
MOT - Drop-weir structures (River Cole)
ARM2 - Fish Passage (Barwon River)

9.1 Implications for flood levels and flood regime.

The water level upstream of a weir is affected by the crest level of the weir, the dimensions of the weir, i.e. its width or breadth across the channel, and the coefficient of discharge which is the ease at which the water passes over a weir crest. If any of these are changed by replacing the weir with a riffle, the impact on the water level upstream should be checked.

9.2 Impacts and risks

Types of techniques:	**Risk of increased flood levels**			**Impacts**
	High	**Med**	**Low**	
Replacing weirs			✓	Unlikely to have an adverse impact on capacity. Risk usually low if riffles lower than existing weir (often is the underlying rationale for the works).

9.3 The need and requirements for modelling

Types of techniques:	**None required**	**Hand calcs**	**CES**	**ISIS/INFO WORKS**	**Comments**
Replacing weirs	✓	✓	✓		Initially use hand calculation to show difference between upstream level for a weir and riffle.

Generally the upstream riffle crest should be lower than the weir crest as this will be the structure which will influence upstream levels. The riffle itself is likely to be of a rougher surface texture than the weir, so if the weir crest height and riffle crest height are the same, this increase in roughness will mean that there will be a higher level of water upstream of the weir for the same amount of water passing over it, giving a higher coefficient of discharge. Reducing the riffle's crest to below 80% of the weir crest would usually compensate for this but this should be checked using a simple equation for a weir which can be found in many texts (Herschy, 1985). The riffle could be represented by a triangular profile or crump weir with the equation

$$Q = C_v C_d \sqrt{(g)} b h^{2/3}$$

Where;
Q is discharge or flow (m3/s),
Cv and Cd are discharge coefficients (look-up tables in texts),
g is acceleration due to gravity (9.8 m/s^2)
b is width of weir or riffle crest and
h is depth of water over the crest level.

From this equation the depth of water upstream of the riffle for a given flow can be calculated. This can be compared with the calculated value of depth for that same flow over the weir where a similar equation can be used depending on the type of weir e.g broad crested, crump etc. These equations can be found in Herschy, 1985. In many situations if the simple equations are used to calculate upstream level in this way then modelling is often not needed.

The impact of the riffles can be modelled using the CES package and treating the riffles as changes in sections as described above in the section on introducing riffles and gravel beds

Data needed
Discharge, discharge coefficient and width of crest for the equation;
or
Cross-section topography (before the riffle and after the riffle);
A comparison of the stage discharge relationship of the two sections.

Resources £ (£) £ £ £
Simple equation solving using look-up data;
or
The time taken to collect the data for cross-sections on a reach over a few hundred metres would be 1 day and then 1 day for analysis using the CES.

In some situations the water level downstream of the first riffle is raised by subsequent riffles. Although this is a local impact the rise in water level will be equivalent, at low to medium flows, to the riffle crest height above the original bed level. The impact of these raised water levels should be checked within the local area. At high and flood flows the riffles will be drowned out and not have an impact. In this situation the riffles can be modelled as described above using the CES package.

9.4 *Case study; the River Welland at Harringworth*

On the River Welland, a defunct weir was removed, primarily to improve fish passage, replacing it with a number of riffles utilising the difference in hydraulic head.

Riffle location on the Welland

As there is no available information on the level of the weir before the restoration, it is more difficult to compare the restored reach with the pre-restored condition. However based on qualitative information we can use the hand calculation method for weirs to look at the levels.

9.4.1 Hand Calculation

From observation of the site and the bank level at the location of the original piled weir, the structure was probably of the order of 2m above the bed level. The riffles are of the order of 0.5m above the bed level. As this is 25% of the height of the original weir there will be no problem with raised water levels, more with reduced water levels!

9.4.1.1The old weir

To check the levels upstream of the weir we would use the equation from Herschy, 1985 for a thin plate weir, as it was a piled weir construction:

$$Q = \frac{2}{3}\sqrt{(2g}C_d bh^{\frac{3}{2}}$$

flow (Q) of 1 cumec
b is the width of weir which is approximately 10m,
the suggested value, after Herschy (1985) of Cd is 0.6

The equation can be rearranged to give the depth of water above the crest upstream;

$$h = \left[\frac{3Q}{2C_d \sqrt{(2g)} b} \right]^{\frac{2}{3}}$$

substituting the values

$$h = \left[\frac{3*1}{2*0.6*\sqrt{(2*9.81)}*10} \right]^{\frac{2}{3}} = 0.147m$$

So the depth of water upstream assuming that the weir is 2m high is 2.147m. With a channel slope of 0.00091 we can work out the extent of the backwater upstream using;

$$0.7*\frac{depth}{slope} = 0.7*\frac{2.147}{0.00091} m = 1651m$$

So the backwater would have extended 1.65km upstream of the weir for a 1 cumec flow.

9.4.1.2 The new riffle

The same calculation can be applied for the upstream riffle using the equation:

$$Q = C_v C_d \sqrt{(g)} b h^{2/3}$$

Rearranging this for the riffle to get the water depth above the riffle crest and using the values of width b = 10m, Cv = 1.1, Cd = 0.4

$$h = \frac{Q}{C_v C_d \sqrt{(g)} b}^{\frac{2}{3}} = \frac{1}{1.1*0.4*\sqrt{9.81}*10}^{\frac{2}{3}} = 0.174m$$

So the water level upstream of a riffle crest 0.5m above the bed is 0.674m. This is substantially less than the 2.147m water level above bed upstream of the weir.

The backwater influence from the riffle at 1 cumec flow extends upstream by just over 0.5km as calculated below.

$$0.7*\frac{depth}{slope} = 0.7*\frac{0.674}{0.00091} m = 518m$$

This is again much less than the 1.65km for the weir.

9.4.2 CES

In addition to the hand calculations, the CES is useful in showing the water levels, velocities and flows associated with riffles, simply and clearly. Figures 9a and 9b show cross sections 1 and 2 which are upstream of the 1st and 3rd riffles respectively which were considered. These were the first and third riffles in a sequence of five put in to replace the weir. The first (furthest upstream) riffle was just downstream of the old weir

XS1 Flow (m3/s)	**Elevation (m)**	**XS2 Flow (m3/s)**	**Elevation (m)**
0	-2.894	0	-2.92
0.0478	-2.7666	0.0507	-2.8216
0.2829	-2.6391	0.2696	-2.7232
0.7777	-2.5117	0.6665	-2.6248
1.5754	-2.3842	1.2296	-2.5264
2.6168	-2.2568	1.9484	-2.428
3.8182	-2.1294	2.8147	-2.3296
5.2544	-2.0019	3.7942	-2.2312
6.801	-1.8745	4.8734	-2.1328
8.7016	-1.7471	6.0184	-2.0344
10.4986	-1.6196	7.1061	-1.936
12.7389	-1.4922	8.1948	-1.8376
14.7965	-1.3647	9.5709	-1.7392
17.0818	-1.2373	10.9406	-1.6408
19.7315	-1.1099	12.4797	-1.5424
22.0301	-0.9824	14.037	-1.444
23.5776	-0.855	15.8335	-1.3456
26.369	-0.7275	17.4426	-1.2472
29.438	-0.6001	19.3298	-1.1488
32.711	-0.4727	21.3165	-1.0504
36.1901	-0.3452	23.3968	-0.952
39.8601	-0.2178	25.567	-0.8536
43.7123	-0.0903	27.8227	-0.7552
47.7528	0.0371	30.1616	-0.6568
51.9766	0.1645	32.5816	-0.5584
56.3791	0.292	35.0806	-0.46

Table 9a. River Welland – stage discharge relationships – for both cross-sections. Elevation is relative to a local datum (on bank).

Figure 9c shows the stage-discharge output at the two sections on the date (8/12/04) of measurement. The modelled values match well with the measured water levels. The level measured was -2.45m at a discharge of 1.27cumecs and the model predicted a flow of 1.16 cumecs at that level . The numbers can be interpolated from the stage discharge information given in table 9a. This gives a level of confidence that the model is predicting the correct levels for the flows and we can use it to look at levels at higher flood flows and estimate what flow would be out of bank locally. This would be at just over 20cumecs. This can then be related back to the statistical flows for the nearest gauging station to see how often this flow is likely to occur.

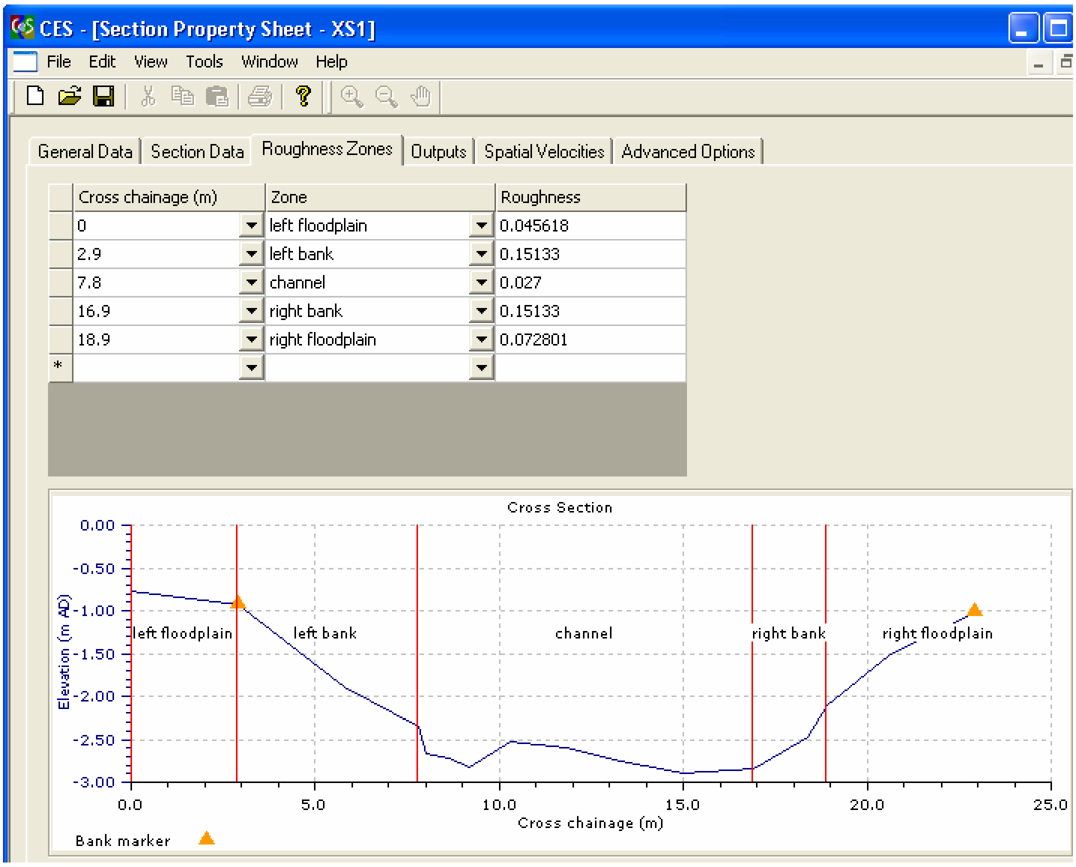


Figure 9a. Riffle at XS1

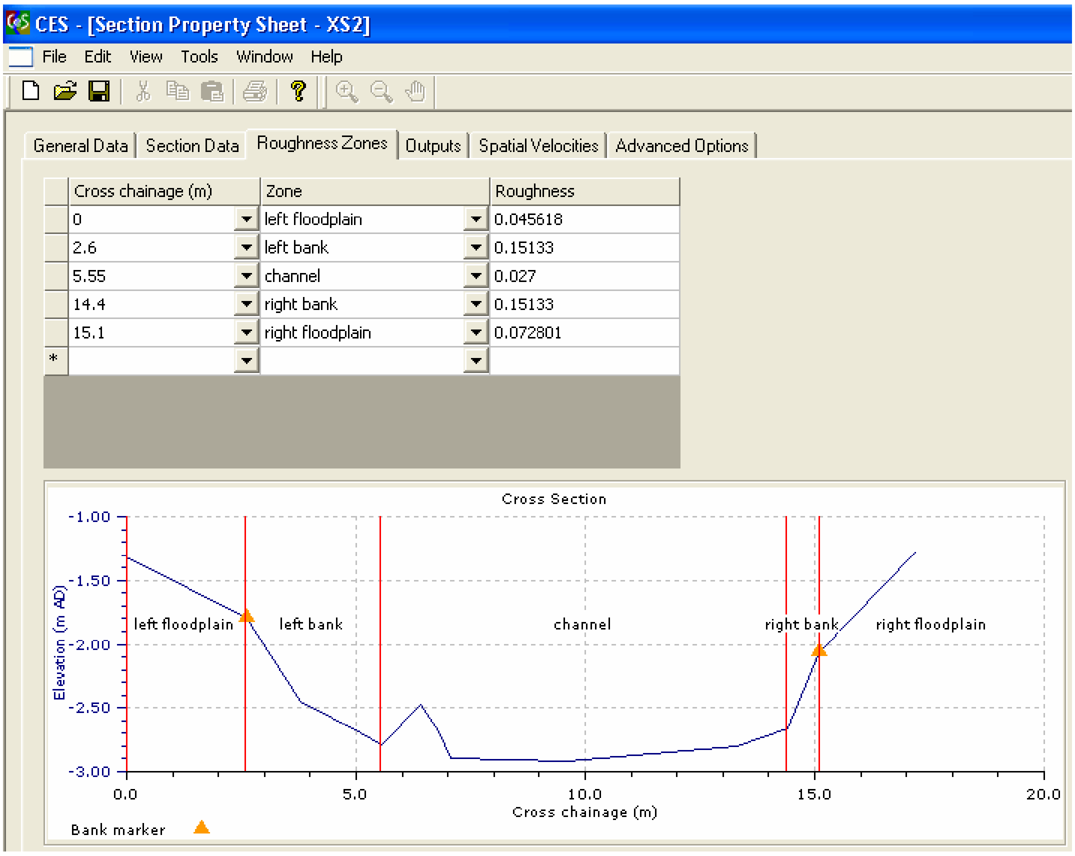


Figure 9b. Riffle at XS2

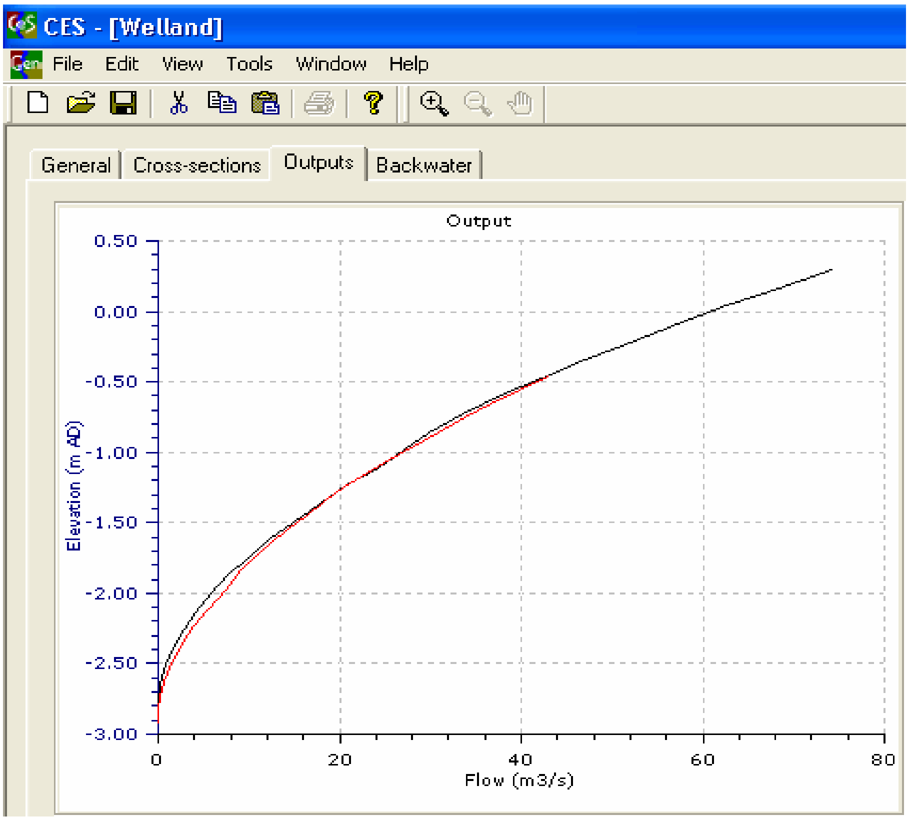


Figure 9c. Stage discharge relationship for the river Welland

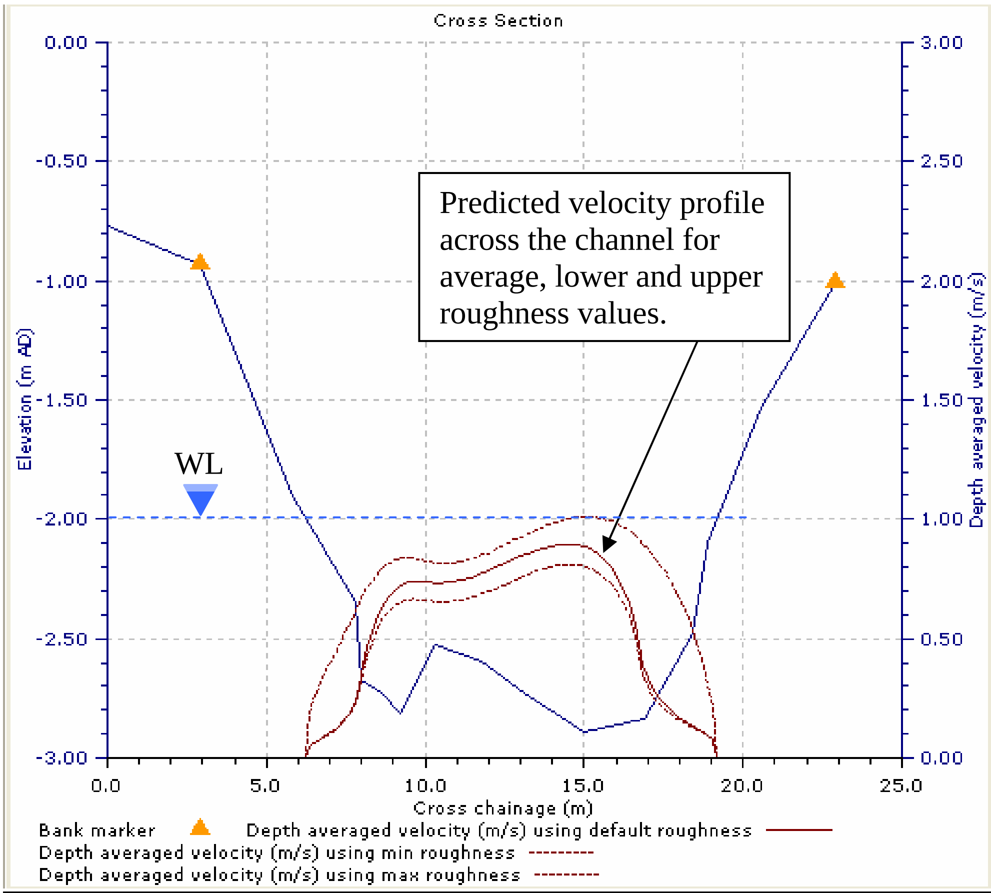


Figure 9d. Velocity distribution over cross section 1

Figure 9d shows the velocity distribution for one of the riffles at the bankful water level of -2.0m AoD. This can help in designing/double checking the correct stone size on the riffle especially if the guarantee of no movement of material is required. Looking at the profile, the size of material would need to be able to withstand a maximum velocity of 0.9m/s. The size of material required to withstand such a flow can be estimated using the appropriate sediment transport equations (Thorne *et al* 1987, Ferguson 1994).

The velocity profile can be calculated across the channel for any water level.

10 Channel re-profiling

Channel re-profiling seeks to restore or recreate the natural cross sectional profile of a river. On many rivers this profile may have been affected in many ways:

Bed

- Deepened by dredging;
- Removal of undulations and natural low/high bed features (e.g. riffles and pools) by dredging.

Banks

- Steepened by dredging;
- Removal of wetland shelves by dredging;
- Vertical lower banks from machine weed cutting;
- Uniform unnatural bank shape (45% trapezoidal slopes) resulting from re-alignment;
- Unnaturally high bank top through bankside spoil deposition or levee creation;

Re-profiling tends to concentrate on the river bank. It is a means to restore/recreate a more appropriate;

- shape,

and often also:

- habitat niches;
- bankside vegetation;
- light or shade;
- safety and access;
- landscape.

All of the above damaging works and their affect on rivers are applicable to Eastern England rivers, as well as most UK lowland rivers. Re-profiling is usually a primary goal or secondary by-product of river rehabilitation in Eastern England rivers. It is also fortunate that the works involved to achieve the restoration/recreation of a more natural bank form almost always have a positive benefit for flood capacity and storage. This is a simple function of the need to remove (cut) material to rework the bank shape. In-filling a bank is difficult to compact and prone to both erosion and pollution of the river with fine sediment.

> If more material is removed than is added, the net result is an increase in cross-sectional area and capacity/storage.

It is important to recognise the intrinsic difference between beneficial bank re-profiling and detrimental channel widening. The latter is what historically counted as channel improvements, and is one of the processes we are trying to reverse. The problem with this ‘solution’ to flooding was that the flood flow capacity was used to calculate the channel size/shape. If the required flood flow was a 1 in 100 year event, it resulted in a massive channel that would only be appropriate for flows occurring very infrequently and for a few days or weeks at most in a whole year. This widening often resulted in a channel bed far too wide to sustain adequate flow depths and associated habitat types at the lower, more frequent flows.

Bank re-profiling in the context of rehabilitation is concerned with at least maintaining the current 'low-flow' width of the channel (often referred to as the Q95 width; where the width of the channel is taken at the water level of a flow whose discharge is exceeded 95% of the time). Using this low-flow width as an indicator, it give a guide that for approx. 95% of the time there will be a reasonable volume of water in the channel to sustain its physical features and communities.

It is common to incorporate bank re-profiling as a mitigating measure for other in-channel works that introduce material or reduce conveyance/capacity. For example, narrowing the channel by 20% using structures that are placed below low water level will have an effect on flows and channel capacity, but by adding works to the bank (say reduction of slope angle from 60% to 30% and removal of 300mm of nutrient rich topsoil/dredgings) a net gain in capacity can be achieved (cut > fill) for bankful flows. If conveyance is also affected, for example replacing a (smooth) weir with a (rough) riffle, additional re-profiling of the flood channel may be appropriate to offset this.

Examples of channel reprofiling

MOT – New meanders one side of existing channel (Skerne)
MOT – New meander through open fields (Cole)
MOT – New meander in an impounded river channel (Cole)
MOT – New channel meandering either side of existing (Cole)
MOT – New meandering replacing concrete weirs (Marden)

10.1 Implications for flood levels and flood regime.

Generally if there is an objective that cut>fill, and assuming spoil is removed from the floodplain, the net result is an increase in flood capacity which can help to offset other works planned in the channel.

Upstream impacts are likely to be increased velocity and lowered levels if cut is much greater than fill. Downstream impacts may also be lowered levels for high flows but increased water levels where channel profile goes back to existing.

10.2 Impacts and risks

Types of techniques:	**Risk of increased flood levels**			**Impacts**
	High	**Med**	**Low**	
Channel re-profiling		✓	✓	Low risk if cut significantly greater than fill. Use CES unless unsteady modelling required. Modelling can be used to show benefits.

10.3 The need and requirements for modelling

Types of techniques:	None required	Hand calcs	CES	ISIS/INFO WORKS	Comments
Channel re-profiling	✓		✓	✓	Use CES depending on extent of re-profiling.

In the situation when cut is greater than fill within the channel, and spoil is physically removed from the flood channel, such that the net result is an increase in flood capacity, then it is unlikely that modelling would be required other than for investigating the upstream/downstream impacts and changes in velocity.

Depending on the extent of the re-profiling, using a steady state model can show how the re-profiling will affect the water levels along the channel. The requirement for modelling is dependent on the extent of the work done, the net increase or decrease in the overall channel flood capacity, as explained above, and any implications of increasing flows downstream. The CES software can be used to determine the effects on the water levels locally at a range of flows through the reach affected.

If the re-profiling causes the floodplain to be inundated more frequently and to greater depths then unsteady modelling using one of the 1D models may be required to determine the change in storage characteristics of water on the floodplain and the impacts on the water levels. This may show the positive benefits of water being stored on the floodplain in attenuating flood water.

If there is likely to be an increase in flood conveyance through the reach this may impact on flood levels downstream of the works and a 1D model would need to be used to investigate this. This would require more cross-section and floodplain contour survey and establishing a 1D model of a few km of river which would be several weeks of work in addition to the survey.

Data needed 🖫🖫(🖫🖫)🖫
Cross-section topography (current channel dimensions and proposed dimensions);
Stage discharge relationship;
and
Floodplain topographic mapping if floodplain inundation modelling required.

Resources £ £ (£ £) £
The time taken to collect the data for cross-sections on a reach over a few hundred metres would be 1 day and then 1 day for analysis using the CES.

Additional time would be needed if using an unsteady state model.

10.4 Case Study; the River Rhee at Wendy

The Rhee (Upper Cam) had been historically dredged at this site until the channel was very deep, wide and had little in stream variation. Banks were uneven, having a high left bank where years of dredgings/weed cuttings had raised levels.

The combination of dredgings and deepening had formed a steep high slope on the left bank, over 1m higher than the right bank. The nutrient input to the topsoil from the dredgings, and lack of tree cover on this bank had resulted in a nettle covered slope, with very little native vegetation on the bank or river margin.

Before.
Angle of slope before reprofiling carried out.

During.
Reprofiling results in a shallower bank angle and top of bank set back. Excess material can be seen stockpiled behind the access track waiting to be spread.

The project sought to remove the topsoil and nettle roots allowing seeding of native grasses, shallow the bank to provide a view of the river and to let in more light to aid colonisation of the wet ledge (designed to narrow the channel – described in Section 5)

.

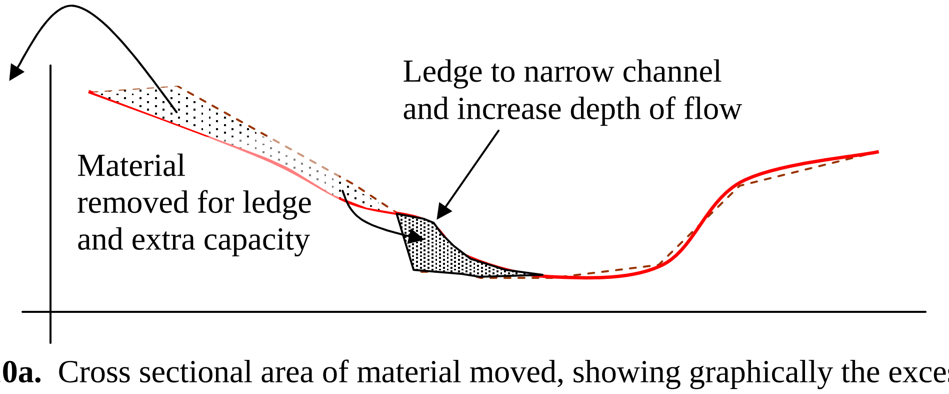


Figure 10a. Cross sectional area of material moved, showing graphically the excess of cut over fill.

The added benefit of increased capacity would offset the ledge creation and should reduce flood levels

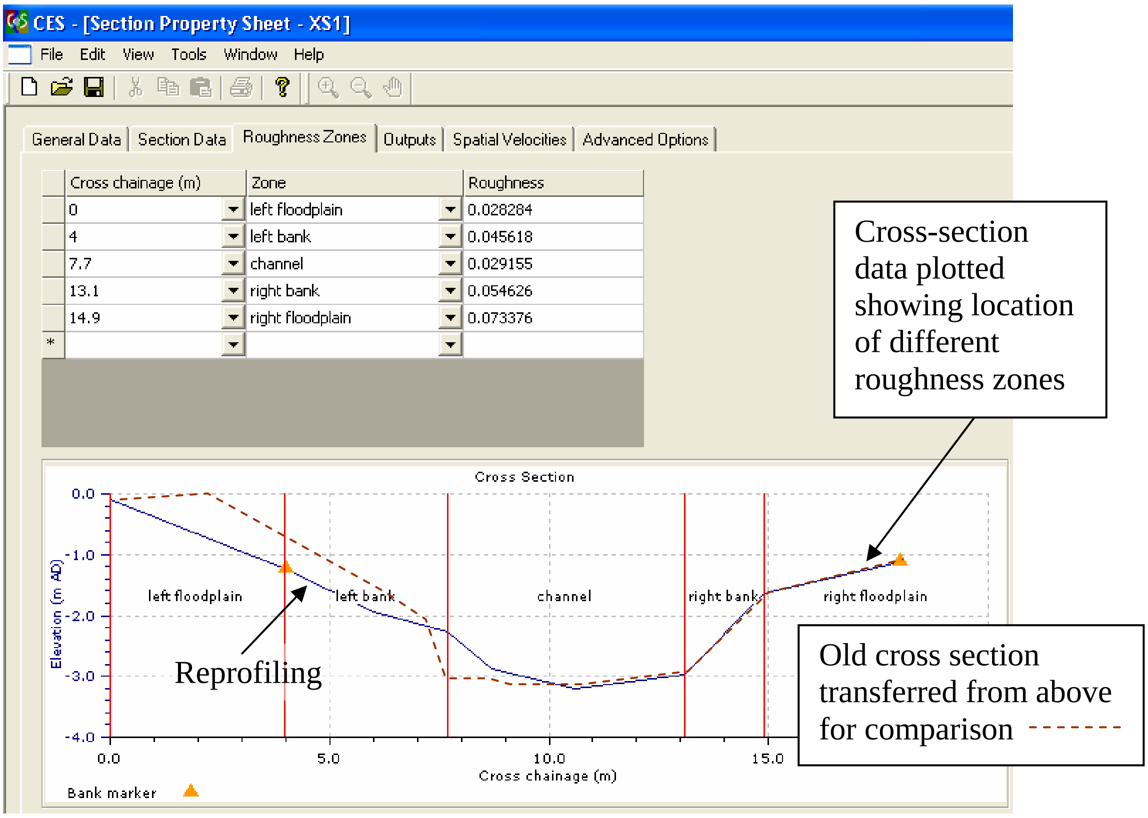


Figure 10b. River Rhee cross section 1, pre and post works.

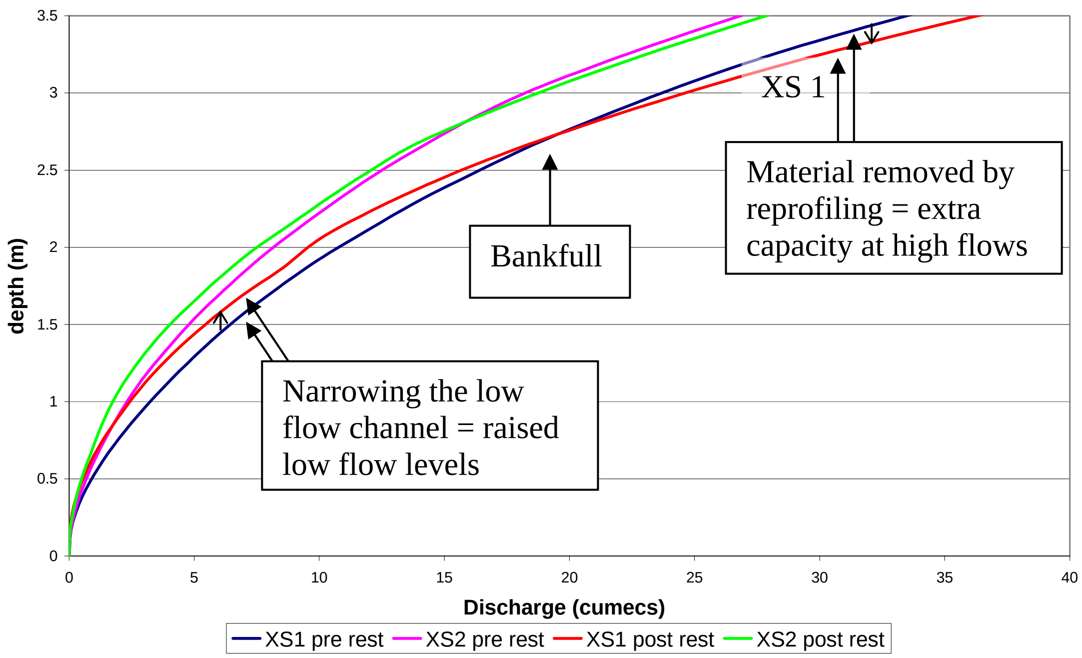


Figure 10c. Stage discharge curve for the River Rhee cross sections.

Figure 10c shows that up to the bankful level, the post restoration channel has a greater depth for the same discharge which is to be expected as the section is being narrowed.

As the water level approaches bankful level this changes and the post restoration depth is lower, at both sections, for the same discharge. This is due to the increased capacity of the channel where the bank has been reprofiled. In this way the reprofiling works has a direct beneficial effect on the capacity of the channel at flood flows, as well as the recognised enhancement benefits stated above.

11 Willow spiling

Willow spiling was given as a commonly implemented river rehabilitation technique, though its main purpose is bank stabilisation and erosion protection. However, spiling using live materials does result in habitat provision (nesting site for riverside birds, trailing limbs for emerging invertebrates and cover for fish). For the purpose of this guidance we shall consider that the spiling is employed to provide both bank stability and riparian bankside habitat.

As with many other erosion protection methods, supporting the banks with integral live materials is intended to provide a long term ‘living’ bank structure. This living structure (grass, marginal plants, shrubs or trees) provides cover, food and shelter, as would a natural river bank.

As the technique is applied to the riverbank and generally involves above ground (so above mean water level) growth, the impact upon flows is usually limited. At high flows and after a decade of growth, a long spiled section could disrupt flow patterns considerably. It is therefore necessary to plan for the maintenance needs of such works.

Examples of willow spiling

MOT – Willow Spiling (Skerne)
MOT – Willow Mattress Revetment (Skerne)

11.1 Implications for flood levels and flood regime.

The inclusion of different materials such as willow spiling or hazel hurdles on a bank of a river will change the roughness of that reach of the river.

11.2 Impacts and risks

Types of techniques:	**Risk of increased flood levels**			**Impacts**
	High	**Med**	**Low**	
Willow spiling			✓	Can change roughness on banks – use CES to study impacts. Assumes regular maintenance programme to keep under control.

11.3 The need and requirements for modelling

Types of techniques:	**None required**	**Hand calcs**	**CES**	**ISIS/INFO WORKS**	**Comments**
Willow spiling	✓		✓		Modelling usually not required unless extensive

By changing the roughness of that reach of the river, it is likely that the impact of spiling will be of the order of up to a few cm in bankful conditions and less in flood flows. It is unlikely that modelling would be required except in areas where the change in bankful water levels are very sensitive, for example along side residential areas.

In the case where small changes in water level are critical, the Conveyance Estimation System is an ideal way at an individual section or along a reach of demonstrating the impact of this change in roughness to the stage-discharge relationship. A typical section where spiling or brushwood are to be included is incorporated in the CES and a roughness profile given to that section through the Roughness Advisor. Changes to the roughness can then be made at the correct position on the section and the impact on the stage-discharge relationship investigated.

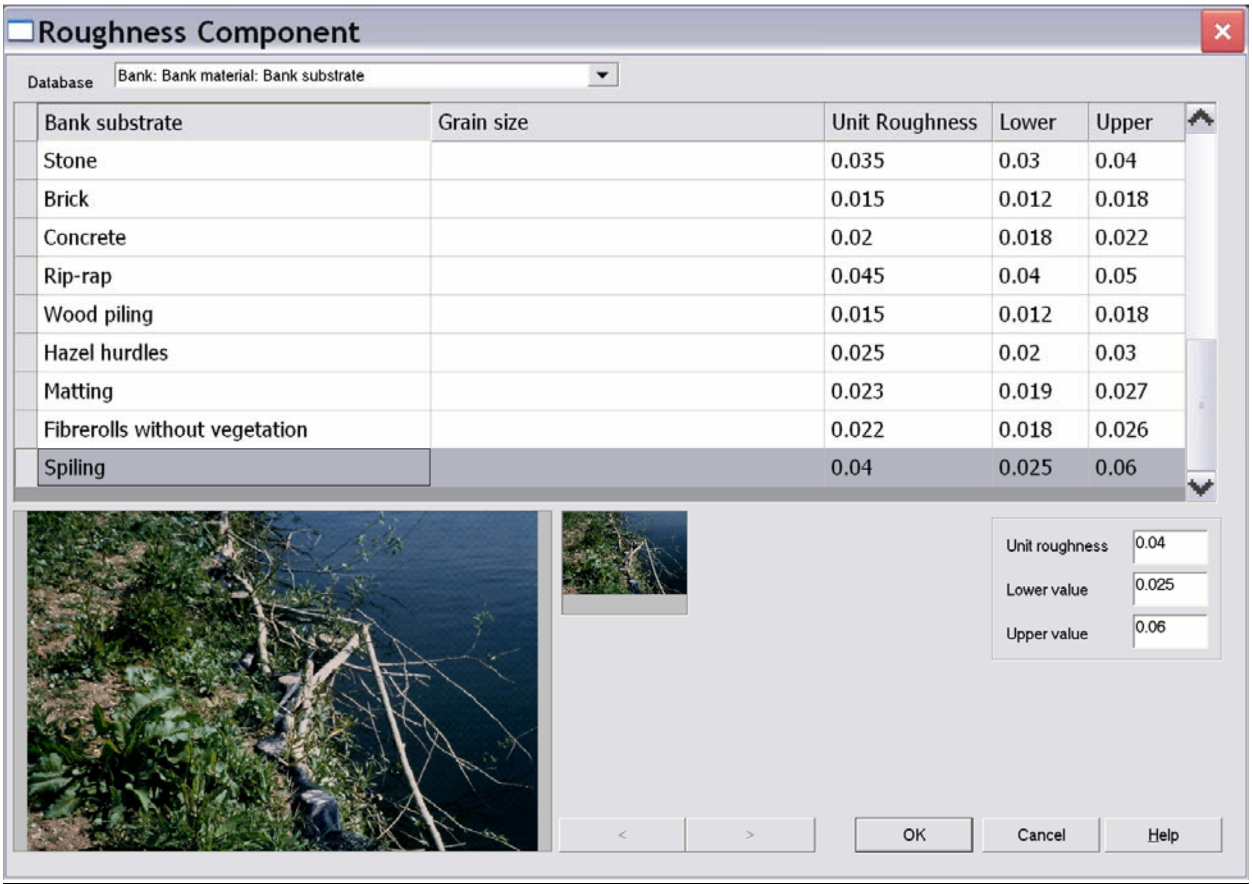


Figure 11a. Willow spiling can be selected within the Roughness Advisor

Data needed 🖫(🖫)🖫🖫🖫
Stage discharge relationship;
indicative cross section;
slope;
photos of the site to compare with the roughness advisor database.

Resources £ (£) £ £ £
This may require 0.5 day of data collection plus 0.5 day of analysis using the CES software.

Will vary if a single section or a river reach

11.4 Case study; the River Brent Rehabilitation Project

On the River Brent, willow spiling and mattressing were used to help stabilise the new meander bends created as part of the rehabilitation project.

The bends were dug and protected, at the toe, with stone (actually crushed, recycled concrete lumps from the previous concrete channel). This provided an immediate protection from outer bend erosion. However, it did not fit with the landscape/habitat requirements of the project. Willow was incorporated into the design to help bind the stone together, provide riparian woody habitat and mask the visual unattractiveness of the concrete.

The crushed concrete protection being installed, and two years later with the willow growth.

12 Woody debris

Woody debris is a catch-all term for anything from a log staked to the bank to huge log jams that completely dam the river. It is likely that in the context of Eastern England's rivers this term is applied to introducing logs into the river.

Geomorphologically, woody debris is an agent that can have a dramatic influence on river form. For example, in North American rivers fallen and floating trees may combine to interrupt river flows, causing bed scour and riffle creation, bank erosion, complete blockages and new resultant channels. In large mobile gravel systems this is likely to have been one of the dominant instigators of morphological change, when combined with bankfull flows. In remote N. American systems there are no risks associated with this; no structures or population concerns.

A woody debris accumulation on the River Enrick, nr Inverness

In managed Scottish gravel bed rivers the trees have often been felled for angling access and fallen trees are quickly removed to prevent damage to bridge piers. This could be one of the reasons why some 'active' Scottish rivers now have very uniform beds with few morphological features.

In Eastern England, woody debris is unlikely to have a dramatic effect on the morphology of the channel as;

- there is less by, and in, the rivers;
- the rivers are low energy;
- too many constraints exist to allow large floating debris and jams;
- erosion is seen as a negative impact, due in part to the narrow corridor (if any) afforded to the river;
- the eroded material is unlikely to be beneficial gravel (more likely to be silt, clay or soil).

In short, introducing woody debris is likely to be restricted to;

- a form of channel narrowing using logs/brushwood as deflectors;
- staking logs to the bed to provide cover/holding areas for certain fish species;
- fixing small trees/part trees/shrubs to the bank to provide bank protection and/or fish cover.

All three can be included within the discussion of other techniques and their impact on flood flows (respectively, narrowing, increased bed roughness and increased bankside roughness).

Example of using woody debris

ARM2 – Re-introduction techniques for in-stream large woody debris

12.1 Implications for flood levels and flood regime.

Similarly to the use of willow spiling, the inclusion of different woody materials such as logs, brushwood or hazel hurdles on a bank of a river will change the roughness of that reach of the river. It is likely that the impact will be of the order of up to a few cm in bankful conditions and less in flood flows.

12.2 Impacts and risks

Types of techniques:	Risk of increased flood levels			Impacts
	High	Med	Low	
Woody debris			✓	Model in CES using change of roughness. Risk is dependent on extent.

12.3 The need and requirements for modelling

Types of techniques:	None required	Hand calcs	CES	ISIS/INFO WORKS	Comments
Woody debris	✓		✓		Usually no modelling required other than when debris is significant when roughness advisor within CES could be used.

It is unlikely that modelling would be required except in areas where the change in bankful water levels are very sensitive, for example along side residential areas.

In the case where small changes in water level are critical, the Conveyance Estimation System is an ideal way, at an individual section or along a reach, of demonstrating the impact of this change in roughness to the stage-discharge relationship. A typical section where logs or brushwood are to be included is incorporated in the CES and a roughness profile given to that section through the Roughness Advisor. Changes to the roughness can then be made at the correct position on the section and the impact on the stage-discharge relationship investigated.

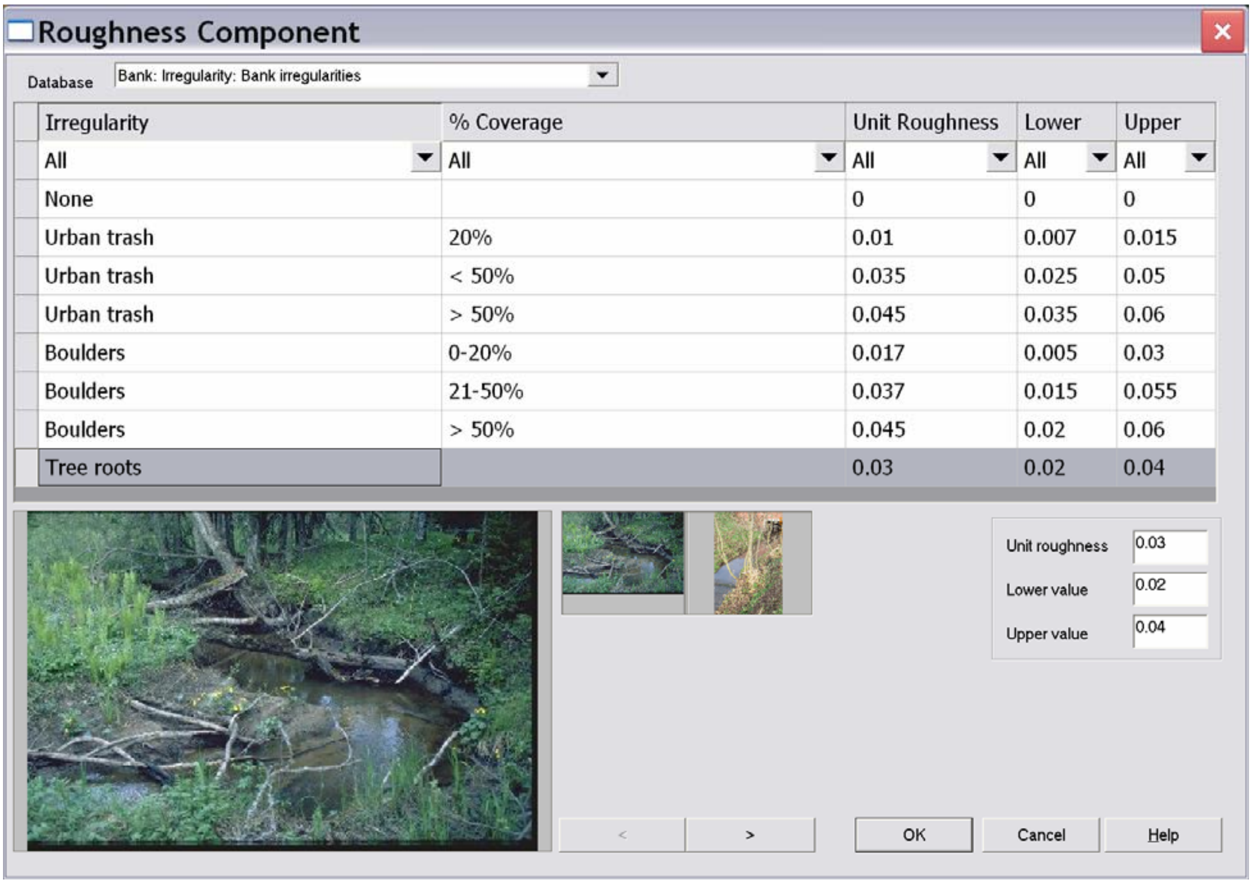


Figure 12a. Woody debris falls under the 'irregularities' section of the Roughness Advisor

Data needed
Stage discharge relationship;
indicative cross section;
slope;
photos of the site to compare with the roughness advisor database.

Resources £ (£) £ £ £
This may require 0.5 day of data collection plus 0.5 day of analysis using the CES software.

Will vary between a single section or a river reach.

13 Fencing

Though not a restoration technique, fences are often included as a by-product of the enhancement work. They are utilised to allow the site to establish and to minimise the disruption caused by grazing animals. For this reason, fencelines are included here to show their effect on flood flows.

In much the same way as spiling or woody debris, a selection of fencelines can be included in a section (an extra roughness zone) to look at the impact on the stage-discharge relationship.

13.1 Implications for flood levels and flood regime.

Fencing can have a big impact on flood flows. Stock fencing is generally poor at letting flows through its mesh. Vegetative 'trash' collects against the fence and can result in the collapse of the structure if it becomes impermeable and acts as a barrier to the force of flood water. This is especially high risk if the fenceline is perpendicular to the flood flow. This can happen where fenclines follow a meandering course, but where the flood flow is across the floodplain.

Generally, farmers erect fences in the direction of flow (knowing too well the cost of repairing them). Even so, the fence will have an impact on flow, much as a line of single trees, one behind the other would cause local changes in flow patterns.

As the direction and construction of the fenceline can differ, the Roughness Advisor has a number of alternatives to choose from, each illustrated by one or more photos.

13.2 Impacts and risks

Types of techniques:	**Risk of increased flood levels**			**Impacts**
	High	**Med**	**Low**	
Fenceline			✓	Model in CES using change of roughness. Risk is dependent on extent, direction and specification.

13.3 The need and requirements for modelling

Types of techniques:	**None required**	**Hand calcs**	**CES**	**ISIS/INFO WORKS**	**Comments**
Fencing	✓		✓		Modelling usually not required unless extensive. Check effect in CES.

Using cross section 1 from the Wensum example (Section 6.5), we can see that the CES adds a roughness zone at chainage 25m for the fence. The fence is given a roughness value of 0.02 by the Roughness Advisor. The section of a river where the proposed fence is to be erected could easily be modelled with and without the fenceline to gauge the effect on stage.

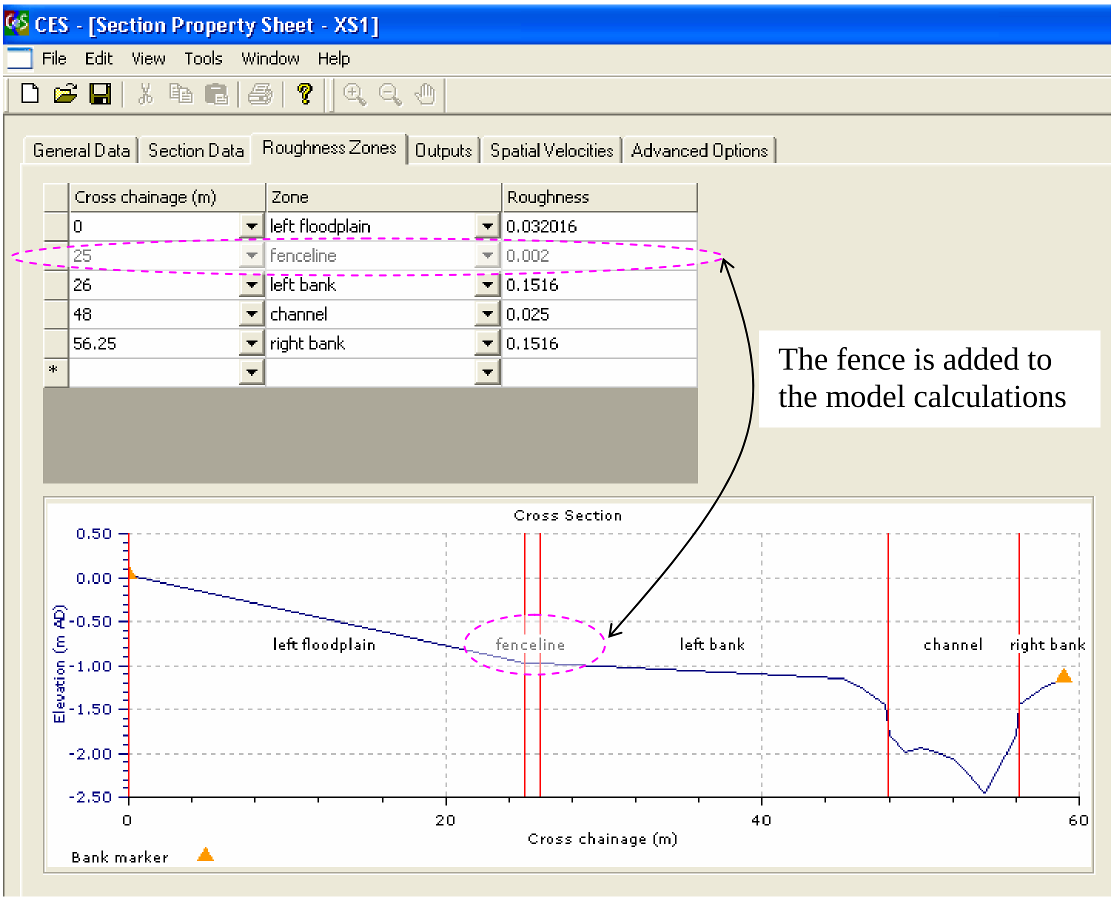


Figure 13a. Crosss section from the Wensum showing the fenceline

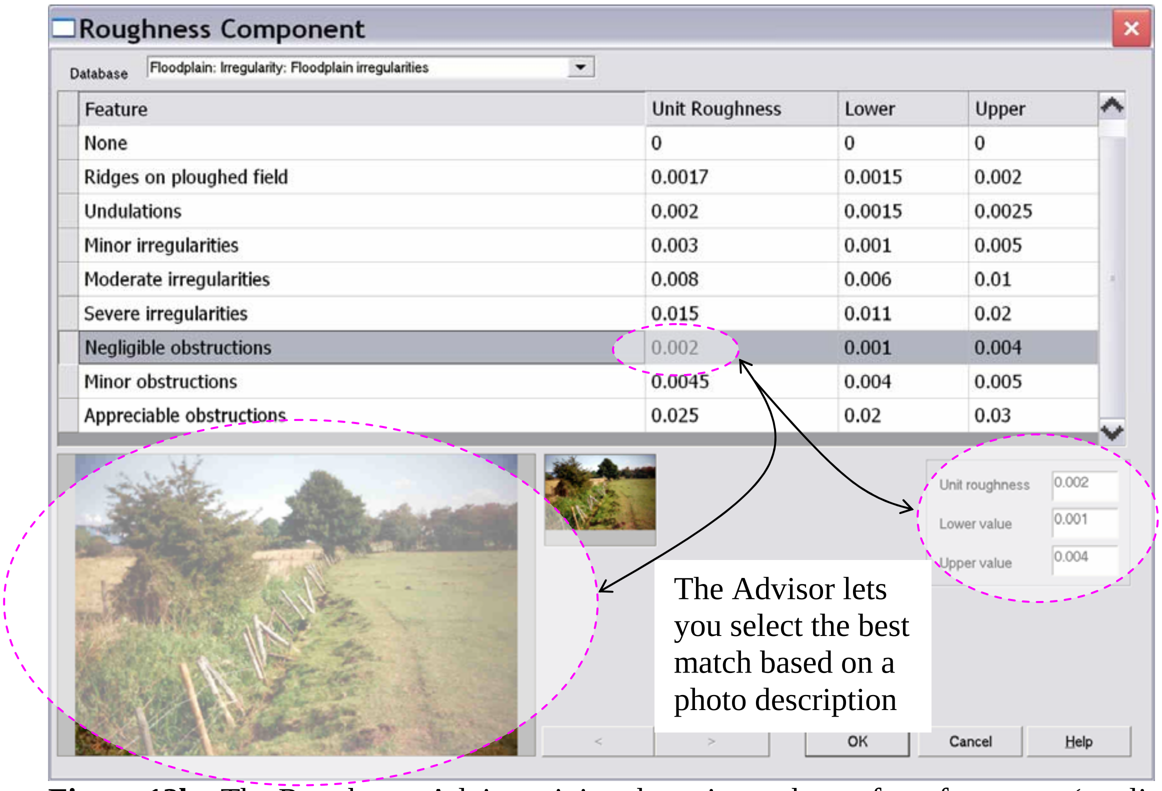


Figure 13b. The Roughness Advisor giving the unit roughness for a fence as a 'negligible obstruction'.

14 Using the CES for a combination of techniques

The previous nine sections deal with individual techniques for rehabilitating rivers. Each is addressed in detail and its effect on the channel illustrated.

River rehabilitation projects will invariably combine a number of techniques to address a number of issues. Although each on its own may have a predictable outcome on flows and levels, together, a suite of techniques may have an entirely different effect. For example, an ill-planned riffle can drown out the benefits of other upstream works.

With care, the CES can be used to look at the impact of one technique upon the other, especially using the long section of the reach.

14.1 Case Study; The River Witham at Claypole

The River Witham at Claypole is a good example of where the CES can be used to good effect to look at the impact of a number of restoration techniques. The river was narrowed using fill material to act as deflectors; natural berms were enhanced by extending and raising; and riffles have been incorporated to add flow diversity and habitat for fish.

Top left
Upstream riffle.

Top right
Natural berm, increased in width and height.

Bottom left
Narrowing below water level with fill material to form a low flow deflector.

Three cross sections where surveyed, an upstream riffle, a central existing berm that had been extended, and a downstream section narrowed with infill material. These were modelled and compared with the three sections measured. The pre-restoration sections are shown below in Figure 14a.

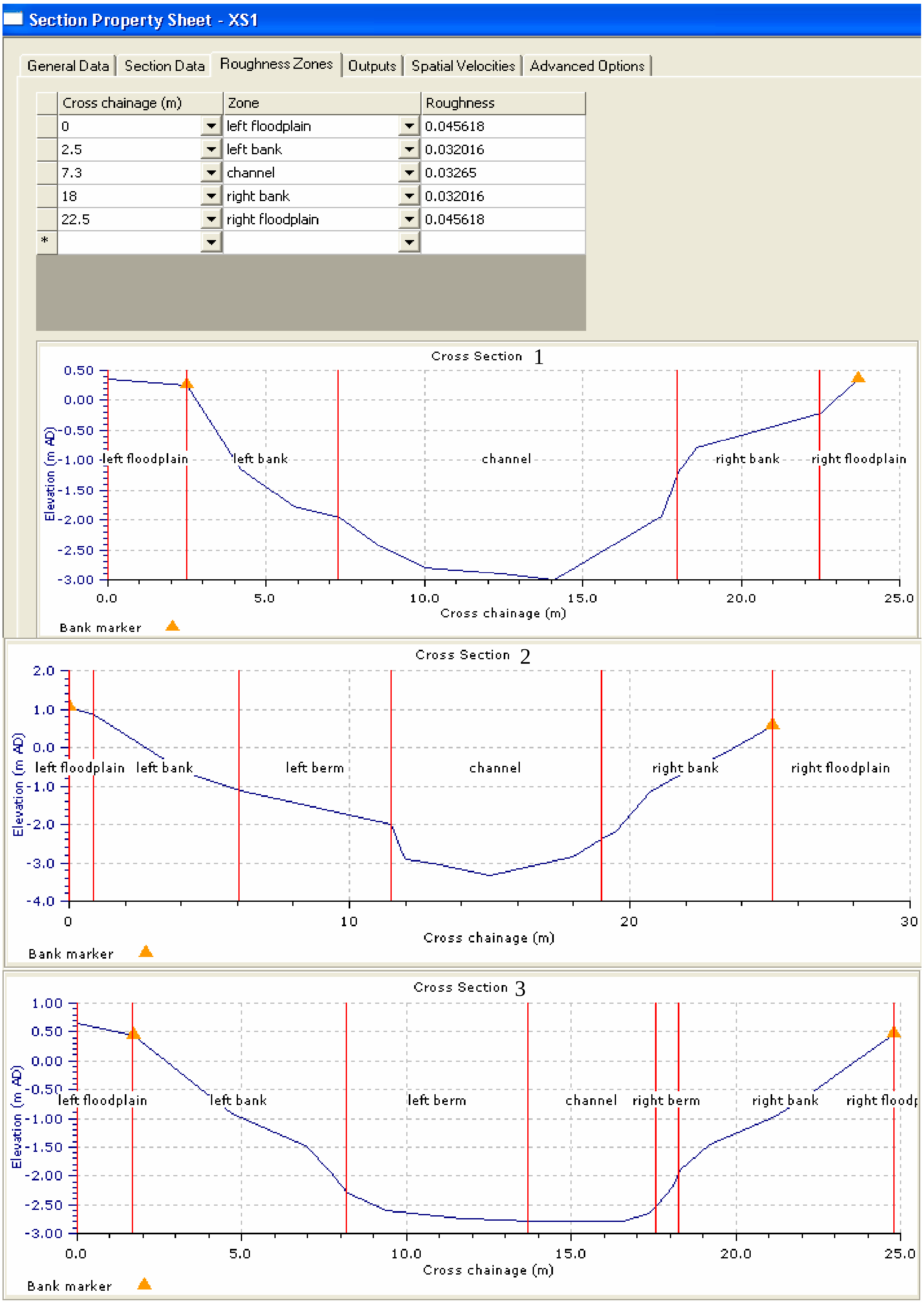


Figure 14a. Cross sections showing pre-works dimensions

Figure 14b shows the post restoration sections. By superimposing the pre works sections we can see that the bed level is raised at section 1 and the widths are reduced at sections 2 and 3.

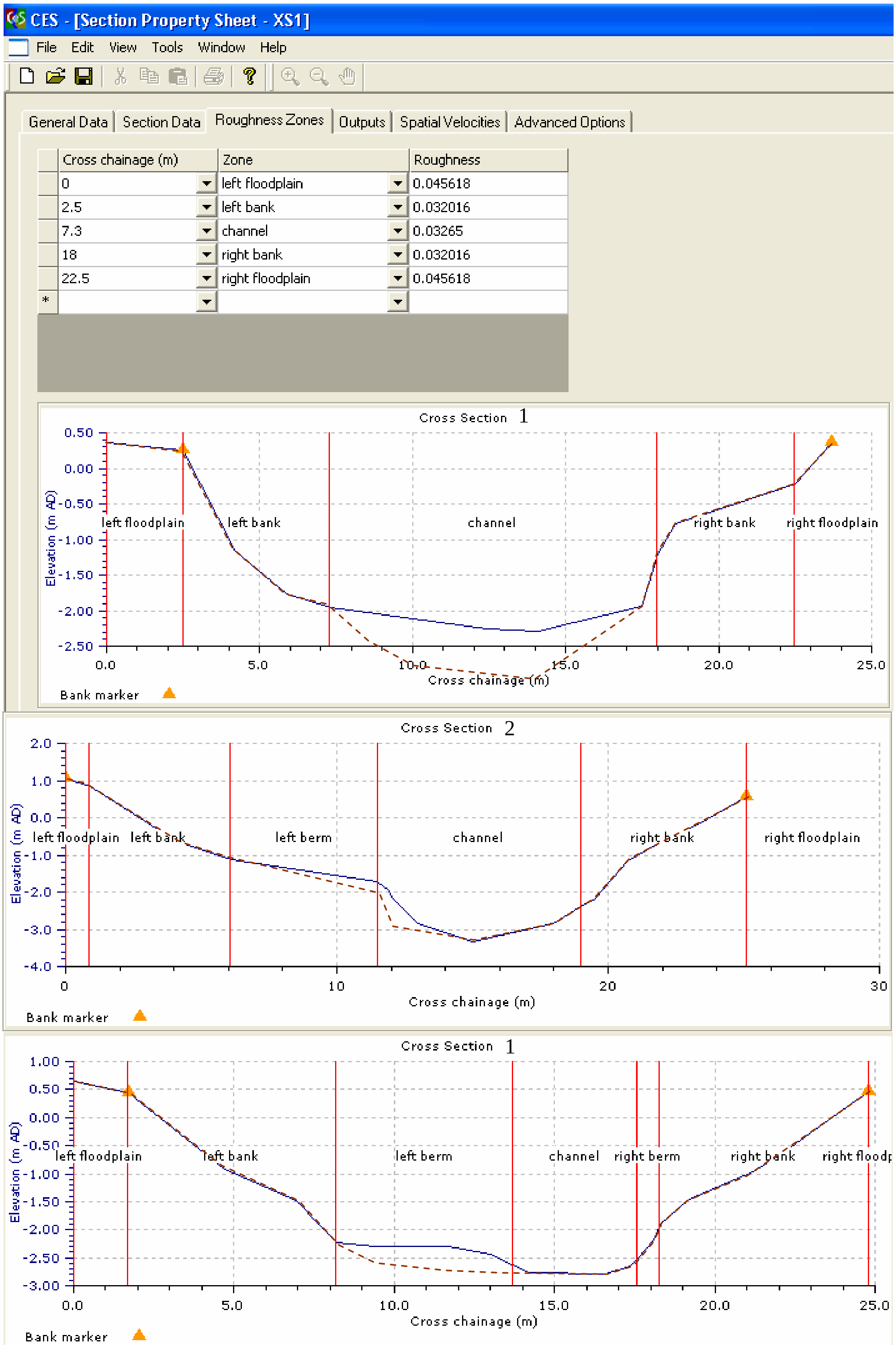


Figure 14b. Cross sections showing post works profiles. Red dotted line is pre works.

The long sections, Figures 14c and 14d, show the river bed (grey fill), water level (blue line) and velocity along the river (green line). Both water level and velocity profile have three readings, based on min., max. and default roughness. For the purpose of this example look at the default (solid blue and green) lines. Viewing the difference between the change in bed level between pre and post restoration we can see that the riffle has increased the bed height at the upstream section by 0.65m. However, viewing the water levels indicates a negligible rise in levels downstream.

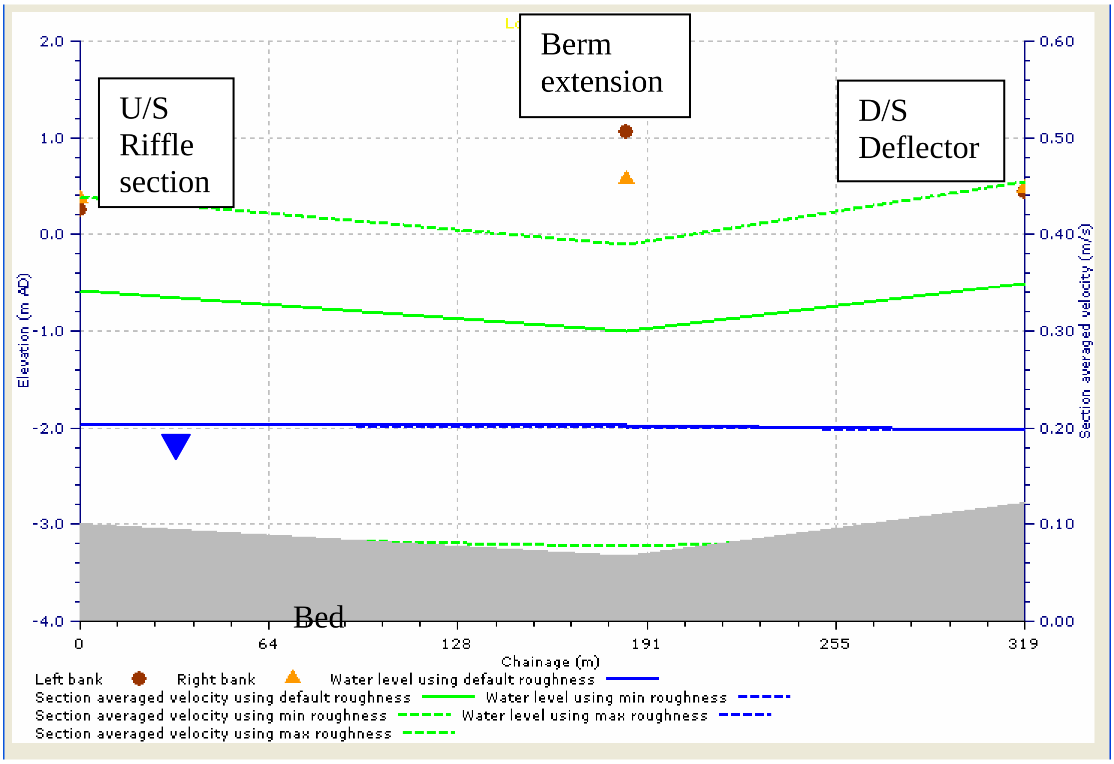


Figure 14c. Pre restoration long section and velocities

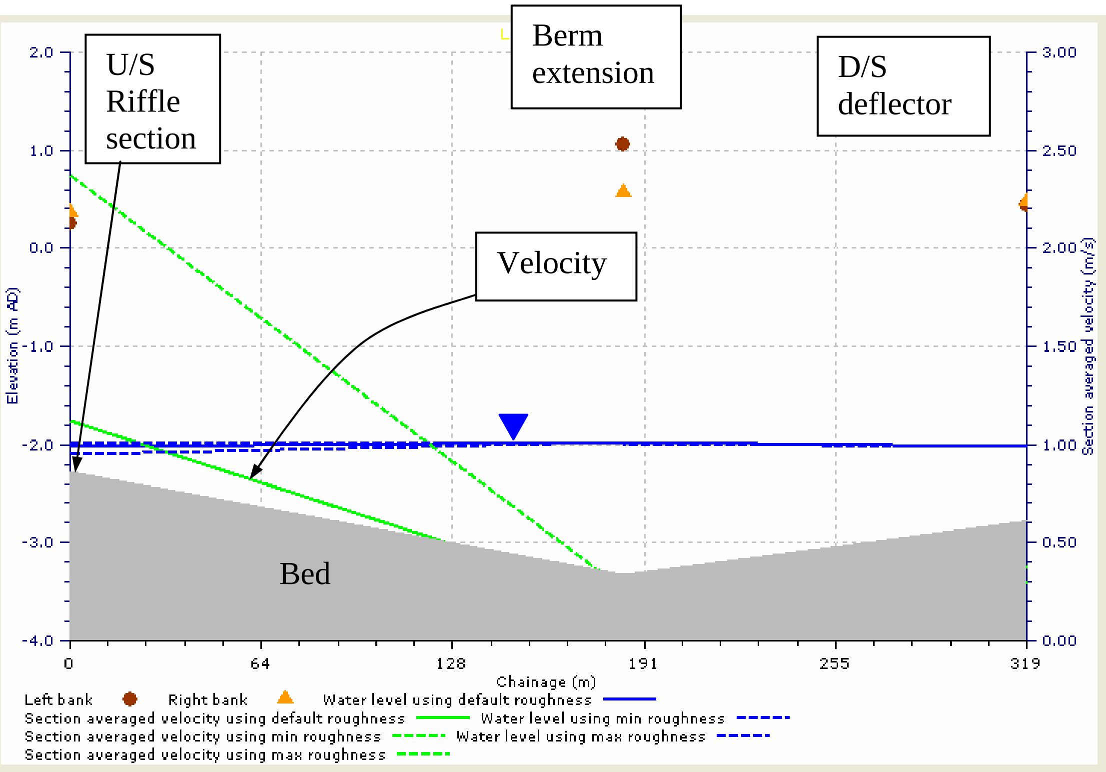


Figure 14d. Post restoration long section and velocities

Although the downstream narrowing does not raise bed levels, it does reduce the channel capacity (Figure 14b). However, again, this change in capacity does not impact on water levels. The works as a whole are predicted not to have had any impact on water levels.

Looking at the velocity line, this shows us that the predicted velocity at each cross section is between 0.29 and 0.35 m/s for the pre works reach; fairly uniform flow velocity. We know that different species at different life stages require a variety of flow velocities, and often it is the diversity of in-channel habitat that dictates this flow diversity. The post works long section, in contrast, shows a far different velocity line. At the riffle, velocities reach 1.12 m/s, compared with similar to pre works readings at the two downstream sections of 0.2 and 0.3m/s.

For both setting and appraising of objectives this information is potentially very useful. The objectives of the project were to enhance the reach to provide better conditions for fish, in particular flow diversity and spawning gravels. The riffle can be confirmed by observation, spawning success predicted from velocity estimates and flow diversity shown by the increased range of predicted velocity readings.

The data collected to generate these results were three cross-sections and slope which took 0.5 days to collect. Data from a nearby gauging station was very useful to check the model results and the analysis took 0.5 day.

15 CES and staff training.

A tool as potentially useful as the CES will need a degree of training to fully explore the possible usefulness for river rehabilitation projects in Eastern England. Until it is fully adopted by and distributed within the Environment Agency, there is little point in advance training for staff, demonstrating its potential uses.

Allowance should therefore be made for staff time and one or more days (depending on need) of RRC time to follow up this report when the tool is available to use. The training will cover the CES software package, work through examples, and should include current examples where staff have been asked to gather the small amount of data needed to run the model.

Throughout the training it will be reiterated that this system is a tool. Its output is only as good as the data collected, and the interpretation of its results is critical. Although the CES is easy to use and simple to apply, the results from the software may be interpreted in different ways and an understanding of hydraulics is required to determine the impact of any results. In addition where the sections for measurement are located, and how much survey information is collected may need to be discussed with staff or advisors who have a more detailed hydraulic knowledge. Whilst one of the ideas of the CES is to minimise the data collection, some data is needed and advise on the best data to be collected should be taken.

Ideally, staff should be in a position to use the CES software to scope the potential for different rehabilitation options. It should provide a method of discarding unsuitable designs and confirming the need for further detailed study. The CES results must ***NOT*** be viewed as a substitute for detailed design and feasibility (where this is required), however it should significantly improve the ability of staff to reach this stage with more confidence.

The ability to model to a basic level the hydraulic suitability of a rehabilitation technique does not equate to it being the best option in that circumstance. For example, a gabion groyne may prove to be hydraulically suitable for narrowing a watercourse in relation to its impact on water depth and flood capacity, but it may fall short of being the best ecologically sound solution.

When preparing reach scale rehabilitation projects (perhaps within a catchment strategy) this added level of detail will enable the project manager to provide Development Control and Flood Risk Management with information on the suitability of the project for the river location, in terms of its implications for low and flood flows, sizing of materials, applicability of techniques, etc.

Even with such a tool to aid concept design, there is still a need to be able to consult with expert advisors when uncertainty is felt, or as a double check on the scheme design.

RRC's Agency National Contract (NATCON 10379) agreement enables all Agency staff to access expertise in relation to river rehabilitation and enhancement.

16 Summary

River rehabilitation and enhancement of Eastern England rivers is already well established. Environment Agency Fisheries, Recreation and Biodiversity (FRB) staff have delivered and are delivering significant habitat biodiversity gains through this work. As schemes become more numerous and complex, assessing their contribution to river basin management and restoration becomes more important.

Project managers will need to access greater resources of information and build internal expertise to aid understanding and justify the proposed works within the regulatory framework of the organisation.

River hydraulics

A major constraint to many river projects is the effect of works on the flow hydrograph and water levels, especially at very low and high flows. Works within channel and on the floodplain will alter the hydraulics of the river (channel roughness, capacity, turbulence, flow pattern) which will in turn impact on sediment dynamics and frequency of out of bank flows (floods). Section 3 discusses the current suite of hydraulic modelling available to determine the effect of single, or a suite of, techniques/structures/measures on the river. One, two and three dimensional models are covered and the application and usefulness of each discussed. FRB staff should have this basic overview of the available models and their potential for use in schemes, and associated resource implications **(Table 3a)**.

Table 4b summarises the potential water level increase and risks associated with the key rehabilitation techniques highlighted in this guidance. This gives a rough guide to the general suitability of these techniques to different situation.

For the majority of schemes, a 1D model is the most that would usually be required to provide information on the impact of a scheme. Two and 3D models provide extra detail, but usually at a level beyond the requirements of flood modelling, and are more difficult to justify in term of cost.

Conveyance Estimation System

The Conveyance Estimation System is discussed as a means for providing an indication of channel conditions under different scenarios requiring limited and basic data. The user interface is more accessible than current hydraulic models, and with training it could prove a useful tool for FRB staff. Flood Risk Management staff will have access to the software as part of ISIS, thus it will be a standard Agency application. **Table 4c** looks at the suitability of the commonly used 1D models and the CES for the different techniques. It provides a quick indication of what level (if any) of modelling is likely to be required.

Allowance should be made for staff time and one or more days (depending on need) of RRC time to follow up this report when the tool is available to use. The training will cover the CES software package, work through examples, and should include current examples where staff have been asked to gather the small amount of data needed to run the model.

Rehabilitation techniques

Techniques for rehabilitation of Eastern England rivers are numerous. Appendix A gives a substantial list of available techniques for river restoration, rehabilitation and enhancement. The majority of these will apply to Eastern England rivers. Those that do not tend to be non-European derived examples (e.g. log dams and vertical pin ramps, from the Australian manual).

Techniques and guides/manuals have been listed in **Table 1a** for reference by Agency staff. The most popularly used three are the UK RRC Manual of River Restoration Techniques (MOT), the US Stream Corridor Restoration Guide (SCUS) and the Australian Rehabilitation Manual (ARM2). The others are also valuable reference texts with case studies, examples and explanatory material.

Agency staff involved in river rehabilitation work should have access to the majority of these texts, either on-line or as hard CD/copy.

The restoration techniques which are commonly applied to Eastern England rivers have been identified by Agency staff as:

- narrowing (including deflectors);
- riffles/gravel bed;
- backwaters;
- reconnecting remnant meanders;
- replacing weirs;
- channel re-profiling;
- willow spiling;
- woody debris;
- fencing.

To guide staff on the most appropriate techniques to use, their uses and limitations, possible impacts and modelling requirements, this document treats each technique in a stand-alone section. The individual technique is illustrated where possible with a case study using the CES, from Anglian Region rehabilitation projects.

Staff Training

Training for staff is essential to ensure that this tool is understood and its inputs and outputs are interpreted correctly. RRC can help provide such training once the CES software has been approved for internal use by staff. Whether the CES is used by FRB trained staff or not, it is suggested that any outputs should be treated as indicative. This software should not be seen as a substitute for years of experienced judgement, but as a further tool. It would be necessary to get Flood Risk Management confirmation where appropriate, and may still require the input of experienced advisors to determine whether the suite of works suggested is the most appropriate.

River Restoration Centre Advice

Further information, queries relating to this guidance and specific advice should be sought from the authors through the River Restoration Centre. RRC's Agency National Contract (NATCON 10379) agreement enables all Agency staff to access expertise in relation to river rehabilitation.

17 Glossary of Hydraulic terminology

Backwater effect The "backing up" effect on the water which is caused by a structure, bridge or other obstruction in the river.

Calibration Adjustment of a model to reach an acceptable degree of accuracy.

Conveyance Measure of the discharge carrying capacity of a channel K m^3/s at a given depth and slope.

Hydraulic model A model for representing the movement of water through a river system and associated floodplain

Rating curve Graphical representation of relationship between depth (sometimes termed stage) and discharge

Resistance Impedance of normal water flow, defined as flow-, form-, frictional, turbulent etc.

Roughness The effect of impeding the normal water flow of a channel by the presence of a natural or artificial body or bodies, bed substrate, biotic eg vegetation, or abiotic/mineral, e.g. bank.

Shear stress The stress at the region close to the boundary between a solid surface and the water or between two different water bodies

Steady state The flow through the river does not vary or change with time

Stage discharge relationship Relationship between depth (sometimes termed stage) and discharge

Unsteady state The variation of flow through a river with time.

18 References

Williams P., Biggs J., Whitfield M., Thorne A., Bryant S., Fox G., Nicolet P. (1999) *The Pond Book - A Guide to the Management and Creation of Ponds.* Ponds Conservation Trust (100pp)

Clayton, C.H.J. (2004) *Land Drainage from field to sea.* Longaston Press

Downward, S. and Skinner, K. (2005 Working rivers: the geomorphological legacy of English freshwater mills. *Area 37.2* 138-147

Hawkins, T.D. (2000) *The drainage of Wilbraham Fulbourn and Teversham Fens* TD Hawkins, Greyfiars, Cambridge

Hodgen, M.T. (1939) Domesday watermills *Antiquity, 3,* 261-79

Ferguson, R. I. (1994). Critical discharge for entrainment of poorly sorted gravel. *Earth Surface Processes and Landforms, 19*, 179-186.

Thorne, C.R., Bathurst, J.C., Hey, R.D. eds. (1987). Sediment Transport in Gravel Bed Rivers. John Wiley and Sons, 995 pages [ISBN 0-471-90914-9]

For all other Manuals and guides listed in this text, refer to Appendix B

Appendix A. Techniques listing

Listing of all techniques found within the manuals and guides in table 1a. Highlighted entries are not of UK origin and should be treated with caution when being considered for the UK. They may not be appropriate for this geographic region or may be older methods, now not seen as best practice.

Techniques	Publication*
1. Restoring Meanders to straightened rivers	
Meander reinstatement	RRTH HAHP
New meandering channel through open fields	MOT FWMG
New channel meandering either side of existing	MOT
New meander in an impounded river channel	MOT
New meanders to one side of an existing channel	MOT
New meandering channel replacing concrete weirs	MOT
Opening up a culverted stream	MOT
Reconnecting remnant meanders	MOT ARM2
2. Enhancing redundant river channels	
Creation of backwaters	MOT NR&WH
3. Enhancing straightened rivers	
Multi-stage channels	RRTH NW&RH HAHP
Stone riffle/permanent riffles	MOT ARM2
Excavation of pools	RRTH CD HAHP
Creation of gravelly shallows/natural riffle form	WTT ARM2 RRTH CD HAHP
Boulder placement (fisheries)	WTT
Boulders clusters	SCUS
Radical re-design from uniform, straight channel to a sinuous	MOT
Replacing a concrete drain with a natural channel	MOT
Creation of online bays	MOT
4. Enhancing over-widened rivers	
Current deflectors (including wing, multiple, straight deflectors and submerged vanes)	MOT
Narrowing with aquatic ledges	MOT
Narrowing through silt removal	NR&WH
Narrowing using limestone blocks backfilled with excavated soil	NR&WH
Narrowing of an over-widened channel using low cost groynes	MOT
Creating a sinuous low-flow channel in an over-widened channel	MOT
Planting water plants - narrow stream/protect banks	WTT

Traditional retards (a series of piles)	ARM2
Pin retards	ARM2
Brush retards	ARM2
5. Enhancing dredged rivers	
Introducing gravel to inaccessible reaches	MOT
Reprofiling channel margins	NR&WH
6. Restoring free passage	
Rock ramp fishways	ARM2
Fish Passageway	SCUS RRTH
7. Provision of bankside and in-channel habitat	
Rock Shelters	SCUS
Lunker structures (cells of heavy woodland planks and blocks)	SCUS
Boulder emplacements/ woody debris and bankside planting (increase fish cover)	SEPAF
Croys	SEPAF
Overhangs	RRTH
Artifical spawning channel (off-line)	RRSH
8. Enhancing the river bed	
Sediment Traps	RRTH
Gravel Traps	RRTH
Gravel Jetting	RRTH
Spawning bed profile	RRSH
Creation of spawning habitat/gravel planting	SEPAF RRTH RRSH RRSH
Gravel loosening	RRTH
9. Revetting and supporting river banks	
Willow spilling	MOT
Willow matress revetment	MOT
Rock revetment	RRTH
Log toe and geotextile revetment with willow slips	MOT
Toe geotextile	WBPG
Plant role revetment	MOT
Grass composites (geotextile/asphalt)	WBPG
Grass revetment	WBPG
Reed planting	WBPG
Supporting bank slips and exposed tree root	MOT
Hurdle and coir matting revetments	MOT
Bank revetment using low steel sheet piling and coir rolls	MOT
Live fasines	ARM2
Woody bank material secured along stream banks	WTT
Rock rip-rap	WTT
Log crib structures (log wall)	WTT
Groynes	ARM2
Benching	ARM2
Longitudinal peaked stone toe protection (LSTP)	ARM2
Faggoting	WBPG
Tree and shrub planting	WBPG
Filled sack barrier	WBPG
Stake and batten/log barriers (barrier to form a breakwater)	WBPG
Pocket fabric/reinforced vegetative bank protection	WBPG

Buffer Strips (Trees/Grass)	FWMH
Log and Christmas tree	FWMH
Retaining barriers (camp sheeting/logs)	RRTH
Dormant post plantings	SCUS
Bank cover structures (solid artifical platforms)	RRTH
Jacks (low-cost stream stability tool)	ARM2
10. Controlling river bed levels, water levels and flows	
Bifurcation weir and sidespill	MOT
Drop-weir structures	MOT
Restoring and stabilising over-deepened river bed levels	MOT
Simulated bedrock outcrops	MOT
Raising river bed levels	MOT
Rock-boulder structures (low dam)	ARM2
Gabion dams	ARM2
Gabion baskets	FWMH
log dams (instead of rocks)	ARM2
Schauberger sills (gentle V-notched weir)	ARM2
Mangfall sills (boulders of arches/ can incorporate a fishway)	ARM2
Vertical pin ramp (increase deposition)	ARM2
Low profile weirs (diagonal, V & drop-over)	RRTH
Low stone weirs	CD
11. Managing overland floodwaters	
Floodplain spillways	MOT
Profiling of land between meanders	MOT
Removing and setting back floodbanks	MOT
Removal of minor embankments/lower floodplains	GRMF
12. Creating floodplain wetland features	
floodplain scrapes	MOT
floodplain wetland mosaic	MOT
13. Providing public, private and livestock access	
Fords and stock watering point	MOT
watercourse crossings	MOT
access paths suitable for disabled users	MOT
Restoring a ford as a atock and vehicular crossing point	MOT
Urban riverside access	MOT
Fencing	ARRM
	FWMH
	RRSH
14. Enhancing outfalls to rivers	
surface water outfalls	MOT
Reedbed at Raglan Stream	MOT
15. Utilising spoil excavated from rivers	
Landforms at keepsafe and Rockwell	MOT
Landform areas	MOT
Cost effective silt removal from an impounded channel	MOT
16. River Diversions	
Diversion of a river valley	MOT
Clay lined river	MOT

* Refer to Appendix B for full publication details.

Appendix B. Guidance manual information

DESIGN MANUALS

Name	Author/Editor	Publisher	ISBN	Date
River Restoration Manual of Techniques*	Richard Vivash (Riverscapes Consultancy) and Martin Janes (RRC)	the RRC	1 902872 00 2 / 1 902872 01 0	1999/2002
The New Rivers and Wildlife Handbook	Ward D, Holmes N, Jose P	RSPB	0 903138 70 0	1994
A Wild Trout Trust Guide to Improving Trout Streams*	Ron Holloway, Simon Johnson and Edward Twiddy	WWT	N/A	2001
A Rehabilitation Manual for Australian Streams Volume 1 & 2 + CD*	Rutherfurd et al	Cooperative research centre for catchment hydrology & Land & Water Resources	N/A	2000
Stream Corridor Restoration Manual ~ U.S. Principles, Processes and Practices*	Federal Interagency Stream Corridor Restoration Working Group	National Technical Information Service (NTIS)	0 934213 59 3 (book) / 0 934213 60 7 (CD)	1998
Waterway Bank Protection: a guide to erosion assessment and management*	Cranfield University	Environment Agency	0 11 310160 0	1999
Managing river habitats for fisheries*	Professor Chris Soulsby	SEPA	1 901322 23 8	
Guidelines for rehabilitation and management of floodplains - ecology and safety combined*	Wolters H.A, Platteeuw M and Schoor M.M (EDS.)	NCR/IRMA	RIZA report: 2001.059 / NCR Publication 09-2001/ ISSN 1568-234X	2001
Habitat Enhancement Initiative (HEI) : Farming & Watercourse Management Handbook (PDF)*	Vyv Wood-Gee,	SEPA/SNH/FWAG/WWF Scotland/SAC	N/A	1998
Restoration of Riverine Salmon Habitats: A Guidance Manual (Fisheries technical manual 4)	Dr K Hendry & Dr D Cragg-Hine	Environment Agency, Rio House, Bristol	HO-11/97-B-BAHB	1997
Restoration of Riverine Trout Habitats - A Guidance Manual	Dw Summers; N Giles & Dj Willis	Environment Agency, Rio House, Bristol	N/A	1996
Handbook for assessment of hydraulic performance of environmental channels - Report SR490	HR Wallingford	HR Wallingford	N/A	2001

Country of Origin	Main focus/discipline catered for	Format	Style of publication	Cost implications to use/buy
UK	A range of disciplines (ecology, fisheries, geomorphology etc..)	web/hard copy	Manual	free on web / ~ £32.50 - £36.50
UK	River management - flood defense, wildlife and river interests	hard copy	Handbook	£19.95
UK	Fisheries	web/hard copy	Guide	£10 + £2 p&p
Australia	A range of disciplines (ecology, fisheries, geomorphology etc..)	web/hard copy/CD	Manual	$25 black and white copy
USA	A range of disciplines (ecology, fisheries, geomorphology etc..)	CD/hard copy	Manual	Hard copy $142 / CDROM $90
UK	Conserving the Land/flood defense	hard copy	Manual	£95
Scotland	Fisheries	hard copy	Manual/guide	free on web
Netherlands	Management for floodplains	hard copy	Report/book	N/A
Scotland	Farming and watercourse management	web	Handbook	free on web
UK	Fisheries (Salmon)	hard copy	Manual	£50
UK	Fisheries (Trout)	hard copy	Manual	£15
UK	Hydraulic performance of channels	hard copy	Handbook	N/A

Ease of accessibility	Ease of use	No of design techniques
linked to direct	Clear, concise, pictorial	11 Parts (~ 47 techniques)
No direct link / need to reproduce	Clear, concise, pictorial	1 Part (Part 3) ~ 14 techniques
No direct link / need to reproduce	Clear, concise, pictorial	1 Part (9 Techniques)
linked to direct	Clear, well-structured	1 Part (Part 3) ~14 types of techniques (volume 2)
linked to direct	not very concise, slightly confusing	1 Part - Appendix Techniques (short summaries)
No direct link / need to reproduce	Clear, concise, pictorial	non-engineering and engineering solutions / Appendix: guide to solutions
linked to direct	Clear, concise, pictorial	8 parts in 1 chapter 7
No direct link / need to reproduce	Colour, clear, pictorial	8 parts
linked to direct	b/w, clear, concise, pictorial	Section 6 - 9
No direct link / need to reproduce	texty, colored diagrams	Split into life cycle stages Part II
No direct link / need to reproduce	b/w, texty, few pictures	Habitat restoration techniques Part 8 (~31 techniques)
No direct link / need to reproduce	Mathematical, graphical, pictorial	Part 3 (numerous techniques)

No of case studies	Applicability to UK rivers	Indication of success	Types of techniques	Links
17 case studies	yes	subsequent performance - subjective	soft-eng / natural regeneration / river restoration	http://www.therrc.co.uk/manual.php
41 case studies	yes	Partially through case studies	soft-engineering / natural regeneration	N/A
7 case studies	yes	Advantages and Disadvantages	river restoration / habitat enhancement	http://www.wildtrout.org/WTT/projects/riverRestoration.asp
within the text/no defined chapter	Some aspects	Appraisal techniques discussed	soft-eng / natural regeneration / river rehabilitation	http://www.rivers.gov.au/publicat/rehabmanual.htm
within the text/no defined chapter	Some aspects	Appraisal techniques discussed	river restoration / habitat enhancement	http://www.usda.gov/stream_restoration/
within the text/no defined chapter	yes	not evident	non-engineering/engineering solutions	http://www.eareports.com/ea/rdreport.nsf/Report/6C8E3F4F40969833802567980058FE58?OpenDocument
within the text/no defined chapter	yes	Partially	soft-eng / natural regeneration / river rehabilitation	http://www.sepa.org.uk/guidance/hei/pdf/fisheries.pdf
2 case studies (Rhine/Meuse)	yes	Yes - Attention points for design	river rehabilitation	N/A
within the text/no defined chapter	yes	not evident	non-engineering/engineering solutions	http://www.sepa.org.uk/guidance/hei/pdf/wwf.pdf
a few within the text/no defined chapter	yes	Critical evaluation of techniques	habitat restoration / rehabilitation	http://www.eareports.com/ea/rdreport.nsf/Report/3B8CBAA6D78C59EB802567980058FD86?OpenDocument
a few within the text/no defined chapter	yes	Drawbacks/effectiveness	habitat restoration / rehabilitation	http://www.eareports.com/ea/rdreport.nsf/Report/5D693E645D929090802567980058FD2C?OpenDocument
a few within the text/no defined chapter	yes	worked examples	non-engineering/engineering solutions	N/A