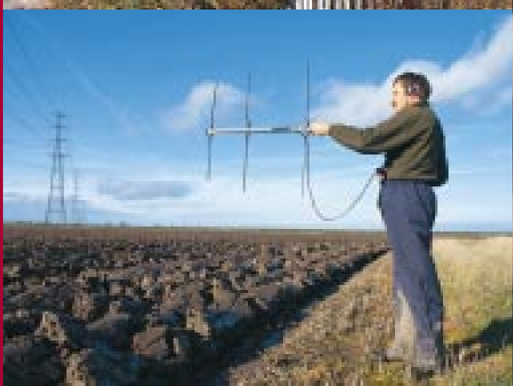
Report Number
685

Geomorphological appraisal of the River Wensum Special Area of Conservation

English Nature Research Reports



working today
for nature tomorrow

English Nature Research Reports

Number 685

Geomorphological appraisal of the River Wensum Special Area of Conservation

D.A. Sear, M. Newson, J.C. Old and C. Hill

ISSN 0967-876X

Project officer	Richard Leishman, Norfolk Team Richard.leishman@english-nature.org.uk
Contractor(s)	D.A. Sear, M. Newson, J.C. Old and C. Hill

This report should be cited as:
SEAR, D.A., and others. 2006. Geomorphological Appraisal of the River Wensum Special Area of Conservation. *English Nature Research Reports*, No 685

Foreword by English Nature

The Geomorphological Appraisal of the River Wensum Special Area of Conservation (SAC) has been jointly funded by English Nature, the Environment Agency and the King's Lynn Consortium of Internal Drainage Boards.

The objective of this work has been to understand the mechanics of the river in order to determine how best the river can be managed so as to benefit the chalk river habitats and species for which the river is internationally recognised. The appraisal involved a detailed fluvial audit to establish the physical nature of the river channel and geodynamics assessments to understand how the river functions within this channel. The report also details a new methodology designed to integrate scientific evaluation of natural geomorphological conditions with data on channel modifications. This multi-criteria analysis is used to extract a set of indices of geomorphic function and morphological condition relative to natural condition. Using these methodologies, the report sets out a geomorphologically unconstrained vision so as to indicate how the river could be maintained and where appropriate restored.

The principle that underlies this work is that providing the physical processes and environmental parameters characteristic of chalk rivers and streams are maintained, then the niches for habitats and species associated with these habitats will also be maintained. This provides an alternative to the approach that has often been adopted in the past of identifying the most bio-diverse areas of the landscape and trying to protect them in isolation from the issues that relate to the wider landscape. So many of the issues that impinge on the environmental integrity of chalk rivers are based on the catchment scale and need to be addressed at this level.

The production of the report on the geomorphological appraisal of the River Wensum SAC takes our understanding of the river to a new level and gives us a valuable new tool in order to develop a vision for its future management.

Richard Leishman
Conservation Officer

Acknowledgements

We would like to acknowledge the help and assistance of a number of agencies and individuals in the provision of data, those participants at the workshop and those who commented on a draft of this report. We are also especially grateful to the riparian landowners along the River Wensum who permitted access to their property for the surveys.

Richard Leishman and Keith McNaught of English Nature managed the contract. A number of other English Nature officers contributed at the workshop, including Chris Mainstone and David Withrington.

We are grateful to many within the Environment Agency for data and comments including Jeremy Bloomfield, Rob Pilcher, Carolyn Penney, Karen Partridge and Jonathan Lampard.

We are grateful to Lou Mayer and Tony Goodwin of the Kings Lynn Consortium of Internal Drainage Boards, and also John Carrick, Chairman of the River Wensum Internal Drainage Board).

Thanks are also due to Andy Brown and Chris Graby (Anglian Water Services Ltd.) for access to detailed sediment records and also Robin Goolden (Project officer of the Wensum Valley Project), Steve Henson (Norfolk Wildlife Trust), Carolyn Penney (Environment Agency) and Roy Church (Chairman of the Wensum Fisheries Action Plan Group) for taking water samples to calibrate turbidity records.

We are grateful to those commenting on the draft of this report including Lou Mayer, Rob Dryden, David Fraser, Richard Leishman, and John Adams.

Summary

This report details an extensive assessment of the fluvial geomorphology of the River Wensum Special Area of Conservation (SAC). It contains guidance on the methods used and the interpretation of the data derived from fluvial audit and geomorphological dynamics assessment. The report also details a new methodology designed to integrate scientific evaluation of natural geomorphological conditions with data on channel modifications. This Multi-Criteria Analysis is used to extract a set of indices of geomorphic function and morphological condition relative to natural. The result is a reach classification of the whole River Wensum against a geomorphological reference condition. This information is then used to derive a set of management approaches to move each reach back towards favourable geomorphological condition. All reach-by-reach information is summarised in this report and accompanying maps as well as within the Geographical Information System (GIS) database.

The results of the assessment suggest that the bed substrates are relic features that are stable at most locations and the geomorphological processes that formed them are no longer operating at the same levels. This makes the river sensitive to human impacts. In general, the river is no longer able to mobilise an active supply of gravels, and features associated with this supply (pools and riffles) are uncommon. Fine sediments inputs from the catchment tend to accumulate within the gravels and there is a lack of natural "flushing".

Fine sediment sources are largely produced from road and field runoff and disturbance of drainage ditches by maintenance. These sources increase the supply to the main channel and have been identified as a target for control and sediment management.

Weed growth in the Wensum is a result of a combination of factors including high nutrient loads, over-widened or deepened morphology, fine sediment accumulation and lack of shade suppression. Where there is over-widening the high fine sediment loads and weed growth promote the development of berms within the over-widened channels.

Management objectives for the channel are related to the expected natural features of a chalk stream or river and the 'missing' features identified through field survey. Long term management of the weed growth will only be achieved through encouragement of shading and reduction in ponding. Such shading is characteristic of the natural chalk stream riparian corridor. Woody debris is also missing from the Wensum; and in its absence there is a reduced potential to create local scour and habitat diversity. Local accumulations of woody debris also increase channel: floodplain connectivity. Management should encourage the retention of the woody debris and the promotion of wooded riparian margins.

Multi-Criteria Analysis approaches have been developed to create indices of geomorphological function (sediment source, sediment sink), naturalness, and modification. This analysis has demonstrated that only 18.9% of the total length of the River Wensum had no documented modification, though this is likely to be an over-estimate.

The report provides reach-based guidance (in both tabular and mapped format) on the form of management required to improve the condition of the River Wensum towards a more naturally functioning river in terms of geomorphological processes. These options should be guided by catchment scale requirements, and it is recommended that sediment ingress should be addressed prior to any physical habitat restoration/rehabilitation or enhancements. In

addition to sediment source control, a condition monitoring plan should be drawn up for all semi-natural/natural and recovering reaches

- Prioritise the restoration/rehabilitation/enhancement on the basis of linking existing natural/semi-natural reaches first.
- Seek to improve those reaches closest to semi-natural conditions.

Work from upstream to downstream within the catchment in order to maximise flood protection benefits and to establish high quality biological drift downstream.

Contents

1 Introduction

The River Wensum is a low gradient groundwater (chalk aquifer) dominated river which flows for approximately 78km through the county of Norfolk, from its source (at an altitude of 75m) on Colkirk Heath (South Raynham) to its confluence with the River Yare in Norwich. In 1993, the Wensum (70.1km of river channel from its source to Hellesdon Mill on the outskirts of Norwich and sections of two tributaries, the Langor Drain and the River Tat) was selected by English Nature as one of 31 rivers in England to be designated a ‘whole river’ Site of Special Scientific Interest (SSSI). The Wensum was selected in recognition of the river being one of the best examples of a naturally enriched calcareous lowland river. In terms of the Joint Nature Conservancy Council (JNCC) River Type classification, the upper river is characterised by JNCC River Type III 'Chalk rivers and other base rich rivers with stable flows', with transitions to River Type I 'Lowland, low-gradient rivers' on the reaches upstream of Norwich. The SSSI designation, which covers an area of 393 ha, recognises the presence of over 100 species of plant, a rich invertebrate fauna, and a diverse fish assemblage (23 species). The SSSI includes twenty parcels of land (which support fen, reedbed and wet grassland) and the river corridor, unusually for a lowland river, is still traditionally managed and relatively natural.

In 2000, the River Wensum was submitted to Europe as a Special Area of Conservation (SAC) under the European Habitats Directive and as part of the European Union’s Natura 2000 network. The total area of the SAC (381.7 ha) is a slightly smaller than the area of the SSSI. The European features for which the site was selected are the biotope, water courses of plain to montane levels with *Ranunculus* vegetation (*Ranunculus fluitantis* and *Callitricho-Batrachion* vegetation), and populations of four species: white-clawed crayfish *Austropotamobius pallipes*, Desmoulin’s whorl-snail *Vertigo moulinsiana*, bullhead *Cottus gobio* and brook lamprey *Lampetra planeri*.

However, the current river channel is the product of a long history of climatic change and anthropogenic modification and management. Prior to any anthropogenic intervention, the river would have been a single channel meandering and multiple-channel anastamosing river with floodplain wetlands and pools set within a mosaic of fen and carr woodland that covered the whole of the floodplain. Since the clearance of floodplain forests for settlement and agriculture some 4500 years ago, the Wensum has been modified such that by medieval times it represented the single thread channel present today. Impoundment of the channel in association with watermills, which began 900 years ago and peaked in activity prior to the Industrial Revolution, has had a dramatic effect on the ecology and hydrology of the system (ECON 1999). The resultant landscape however is of rich ecological and cultural value, the integrity of which will be dependent on the maintenance of a management regime which can support the European features and species of special scientific interest within the constraints of flood risk management.

English Nature commissioned the River Wensum SAC Geomorphological Appraisal in collaboration with the Environment Agency and the King’s Lynn Consortium of Internal Drainage Boards to provide an inventory of the morphological features and to identify and understand the geomorphological processes which influence and control the channel activity, morphological quality and favourable condition status of the river system.

The study area investigated in detail followed the SSSI boundary which included a 70.1 km length of the River Wensum, between Pear Tree Corner (350m upstream of Norman's Burrow Wood; TF 898237) to Hellesdon Mill on the outskirts of Norwich (TG198105) and the lower reaches of the River Tat (3.3 km), Langor Drain (2.1 km) and Guist Drain (0.75 km). The influence of the other major tributaries of the Wensum, including the Blackwater, Swannington Beck, Pennyspot Beck and Wendling Beck are also considered within the audit.

The study has used a standard field methodology, fluvial audit, which consists of:

i) A desk study to collate historical data sources which record changes in the catchment, both natural and anthropogenic, which may have disturbed the fluvial system (discharge or sediment supply), and had direct implications on the channel morphology (change in channel planform, long profile and cross sectional geometry).

ii) A contemporary field survey which integrated the key components of both a Detailed Catchment Baseline Survey (DCBS) and fluvial audit, and emphasised assessment of the controls and extent of erosion and deposition along the channel.

The fluvial audit field survey has investigated the channel morphology, and in particular the presence of sediment accumulation and erosion within the river network. This, together with historical analysis enables an assessment of the stability or dynamics of the river system over time and how this is adjusted to the prevailing flow processes and sediment dynamics. The survey has also related the presence or absence of morphological features to the condition parameters that are identified as habitat preferences for SSSI interests.

In addition, a more detailed Geomorphological Dynamics Assessment has been undertaken to establish; the extent of fine sediment input to the main river network; the grainsize characteristics of the fines stored within the river; the magnitude of fine sediment storage on the river bed; and also to provide an estimate of the ability of the river to mobilise the bed sediments.

1.1 Aims and objectives

The aim of this project is:

To develop, through an understanding of the physical processes of sediment transport, a tool that can be used to develop a vision for river restoration for the River Wensum, whilst balancing these against the constraints imposed by flood risk management.

The specific objectives are:

- to develop an understanding of the geomorphology of the River Wensum in terms of sediment transport processes and resulting geomorphology.
- to evaluate the impact of past and present channel management and modification on natural geomorphological processes.
- to determine a methodology for classifying river reaches in terms of their divergence from natural condition.

- to develop a management plan for the river that aims to enhance the habitat condition for the SSSI/SAC river type whilst recognising the constraints of flood risk management.

1.2 River geomorphology

Thorne (1997) describes the fluvial system in terms of three sets of variables: (1) driving variables, (2) boundary conditions, and (3) adjusting variables or channel form (Figure 1.1). The driving variables of the fluvial system are the inputs of water and sediment, represented in Figure 1.1 as water and sediment hydrographs. Although these variables are often considered to be independent of channel form at timescales greater than a year, this is not necessarily the case. Reach scale adjustment of channel form may control water and sediment flux downstream through changes in available storage, thereby controlling the form of the downstream channel, independent of catchment scale processes.

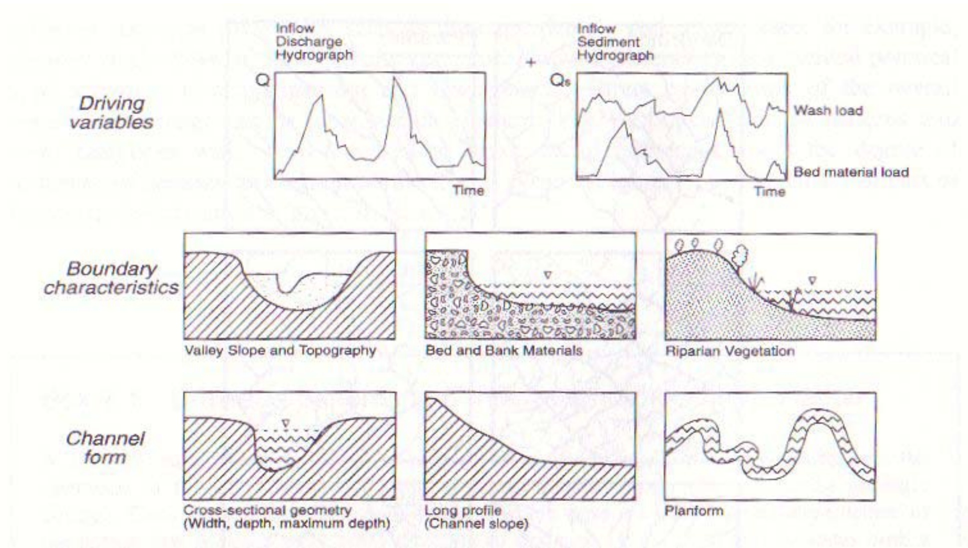


Figure 1.1 Independent and dependent controls on channel form (after Thorne, 1997).

According to this conceptual model of driving variables, inputs, of water and sediment generated from upstream catchment and channel processes, interact with the boundary characteristics to form the channel. These characteristics may be considered as independent variables, inherited by past geomorphological processes, for example the valley slope, and bank materials. The nature of the valley form is significant in that it determines the degree of coupling that exists between the channel system and the valley slopes. In incised, confined valleys the channel may be frequently coupled with the slopes. Channel form will then be influenced as much by slope processes as by channel processes. Harvey (1986) documents the dynamic nature of river channels occupying this type of valley setting in the uplands, and describes switches in channel morphology from braided to meandering and back, largely driven by high magnitude flood events.

As a floodplain evolves, alluvial sediments increasingly form the dominant boundary material, and the river channel becomes increasingly "self-formed". Self-formed alluvial channels have a morphology that results from erosion/deposition processes generated by stream flow. However, this is complicated by the presence of vegetation communities that may significantly influence channel form, and the rates and location of erosion/deposition along an alluvial reach. The interaction between the driving variables and boundary characteristics creates channel and floodplain morphology. These are defined in three dimensions as the channel planform, long profile and cross-section. Alterations in any of these three morphological descriptors, together with sediment size may be defined as adjustment.

2 Methodology

This methodological approach to direct the development of the vision and strategy for restoration is based on:

1) Developing an understanding of chalk river geomorphological processes based on a review of existing literature coupled with specific analysis of the River Wensum.
2) Quantifying, through field reconnaissance survey and existing information on the River Wensum the extent of modification to the river, floodplain and surrounding catchment.
3) Quantifying, through field survey and existing information the characteristics of the physical habitat and channel morphology of the River Wensum.
4) Investigating the sediment transport capacity of the River Wensum and quantifying the sediments available for transport.
5) Utilising GIS modelling to differentiate reaches of varying states of naturalness and physical habitat quality in so far as they support features relevant to the SSSI/SAC status and to identify those reaches that are degraded in this respect.
6) Using a reference condition approach based on the processes and features of natural and good physical habitat quality to specify a design template for those degraded reaches along the River Wensum and to provide guidance on the options for restoration.
7) Considering the sediment transport issues associated with the degradation of the river SSSI/SAC and to suggest options for mitigation.

The River Wensum Geomorphological Appraisal methodology has applied three approaches to the collection and analysis of geomorphological and ecological data:

1) Fluvial audit methodology to understand broad sediment system and channel processes.
2) Geomorphological Dynamics Assessment to understand sediment transport processes in more detail.
3) Multi-Criteria Analysis for the classification of the river network into river modification, management and sediment system categories.

2.1 Fluvial audit

The fluvial audit was conducted following the R+D 661 approach (Universities of Nottingham, Newcastle and Southampton 1998), which uses contemporary (field survey) and historic (archive desk study) data collection methods to gain a comprehensive understanding of the river system. The data requirements for this methodology are presented in diagrammatic format in Figure 2.1 and are documented within the reference, thus are not repeated here. The method is extended by the use of GIS and databases to record the field survey and secondary spatial data information and this forms a key deliverable from this programme.

Extensive documentation existed for the River Wensum and this was reviewed and sifted for relevance to the project aims.

In the field, the methodology included:

1) Field mapping at c 1:2500 (on an enlargement of the 1:10,000 scale maps), which divided the 76 km study reach into a series of smaller homogeneous geomorphological reaches and indicated the specific location of the following attributes:

   a. geomorphological reach breaks.
   b. bank erosion type (including poaching) and severity.
   c. bank protection type.
   d. in-channel modifications (ie weirs, fords).
   e. berm length and average width.
   f. photograph (and bearing for direction).
   g. embankments.
   h. woody debris.

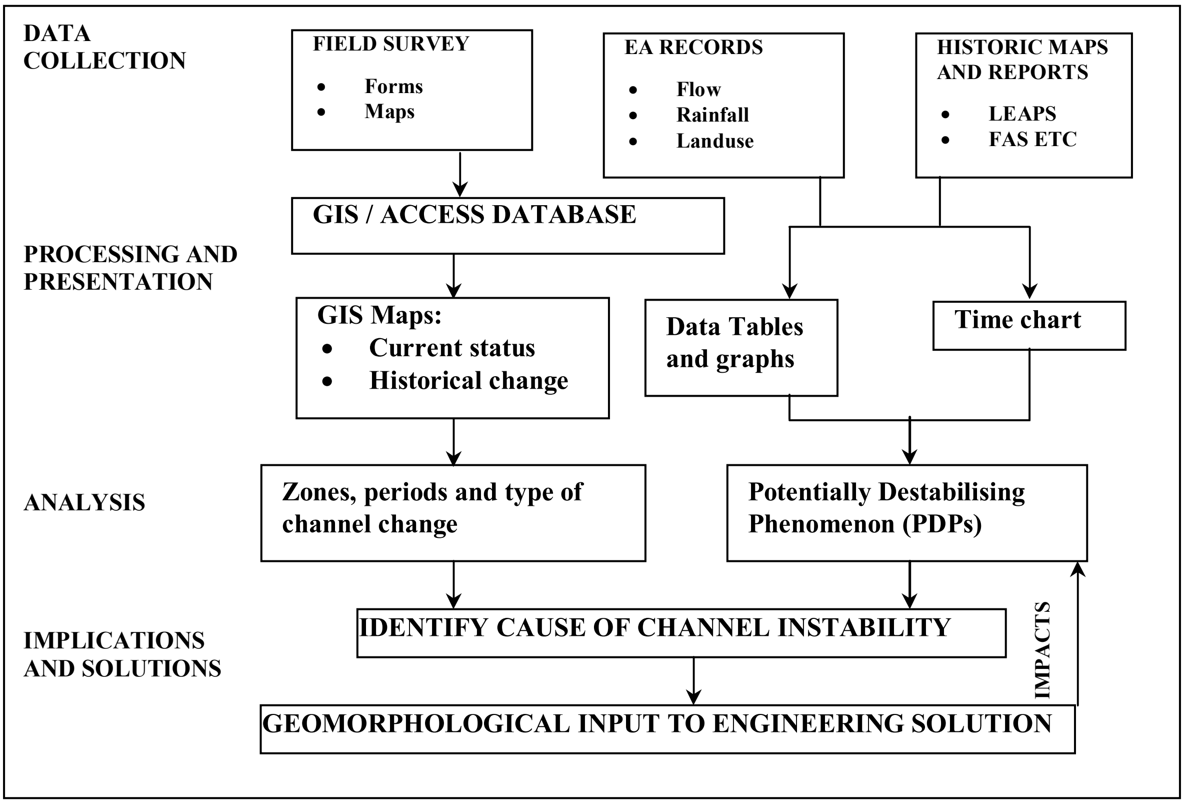


Figure 2.1 Primary inputs and outputs of the fluvial auditing process. (FAS – flood alleviation

2) Field forms, which collated reach-aggregated information on the following:

   a. bank properties (bank height, material type, structure, vegetation cover, erosion process, and toe condition).
   b. channel properties (wetted width, in-channel sediment storage [bar deposition], flow types, anthropogenic controls on hydraulics and bank erosion, and evidence of reach instability [incision or aggradation].
   c. catchment influences (land use and sediment sources)

3) Photographic record which summarises the overall geomorphological character of each reach, and provides detailed visual information on specific attributes or features of the river or modifications to it where these are considered to be of importance in interpreting the controls on processes operating on the River Wensum.

The standard methodology for fluvial audits has been augmented for the River Wensum by the addition of field data parameters specific to SSSI/SAC river systems and particularly the key SAC species relevant to the River Wensum.

A further modification to the standard fluvial audit is the data handling through GIS and databases. Map output is generated from the digital formats and much of the data for further use is held within the GIS, and it is anticipated that this report will be used in conjunction with the spatial data sources and photographic archive. Field form data is entered into an MS Access database and the data linked to the GIS based on the reach polygons defined during the field survey and subsequently mapped in the GIS. Additionally, the field based map data (extent and severity of erosion and the locations of bank protection and modifications and sediment inputs / sources are also created as GIS layers. A number of other data layers are either acquired from secondary sources or created (eg indicative floodplain, conservation designations, historic river channel locations etc).

The full GIS / database implementation of the fluvial audit has been supplied to English Nature, the Environment Agency, and the King's Lynn Consortium of Internal Drainage Boards, along with a full documentation of the data layers generated.

The approach adopted is evidence-based and uses a range of data sources. It is constrained by available information and that which can be reasonably collected during the timescale and resourcing of the project.

The results of the fluvial audit form the bulk of the analysis within this report and are provided as layers within the GIS and database accompanying this report. A separate report is held by English Nature on the GIS and database data layers.

The GIS and database records of the fluvial audit field survey (map based and database field form) and the desk study form the bulk of the data within this report and are provided as digital data files. See Appendix 5 for a copy of the field form. A separate report is held by English Nature on the GIS and database data layers.

Field survey was conducted during the period from November 2004 – February 2005; the extended period was due to the added sediment sampling that was not within the original programme of works.

2.2 Geomorphological Dynamics Assessment

The Geomorphological Dynamics Assessment (GDA) took the form of three separate more detailed assessments of sediment transport characteristics of the River Wensum based on an initial review of the existing documentation, discussion with English Nature local staff, and an initial walk-through survey. These were:

1) Installation of a continuous turbidity probe 20m upstream of Fakenham Gauging Station and collection of bottle samples for calibration from turbidity units into suspended solids loads with the purpose of quantifying the flux of suspended loads over the study period (autumn/winter 2004/5) and reconstruction of longer term records using local turbidity data (Anglian Water records at Costessey) where this was available.

2) Initiation of a storm event monitoring survey undertaken by Environment Agency/Farming Wildlife Advisory Group/Internal Drainage Board operatives following a specific protocol (See Appendix 1) with the aim of identifying and quantifying fine sediment ingress points and sources of fine sediment from the catchment surface over the period of study.

3) Determination of the extent of fine sediment storage within potential spawning gravels.

4) Modelling the mobility of the river bed gravels to determine the ability of the channel to recover from modification and to flush fines from within the river bed.

The results of the GDA are detailed in Section 5.

2.3 Multi-Criteria Assessment

A new approach was developed for this project which permitted analysis, classification and visualisation of multiple data sets based on an index value system. Multi Criteria Assessment (MCA) is an approach that is amenable to GIS modelling and enables combinations of spatial data to be undertaken within a framework of scoring and weighting to represent the relative importance of each variable or variable combination. The choice of variables, combinations of variables and the weighting and scoring of variables/combinations is undertaken using 'expert' input. This framework has the potential to include different stakeholder/expert inputs within the system, although the initial stages have used 'expert' assessment within the context of Favourable Condition criteria for the SSSI. The method is flexible and can be used to communicate the implications of alternative options and provides a relatively simple method of supporting adaptive management. It should also be seen as dynamic – ie new understanding of the Wensum may change the underlying conceptual model and lead to a different definition of Favourable Condition in terms of morphology and physical processes. This needs to be recognised and can be incorporated via the MCA.

The MCA process is outlined in Figure 2.2, and the steps below:

1) Identification of the specific analysis **objectives** or problem (is a site more or less suitable for habitat restoration?).

2) **Selection of criteria** and measures appropriate to the objective derived from field and secondary data (which features are important? – use scientific and or expert opinion).

3) **Scorings** of these criteria (internal assignment of score for each attribute – expert opinion).

4) Allocation of **weighting** (relative importance of the individual factors – between attributes).

5) **Interpretation** of the results (relative to uncertainties and sensitivities).

The outputs from the MCA are detailed in section 4.0 and form the basis for the identification of reaches requiring different forms of habitat management.

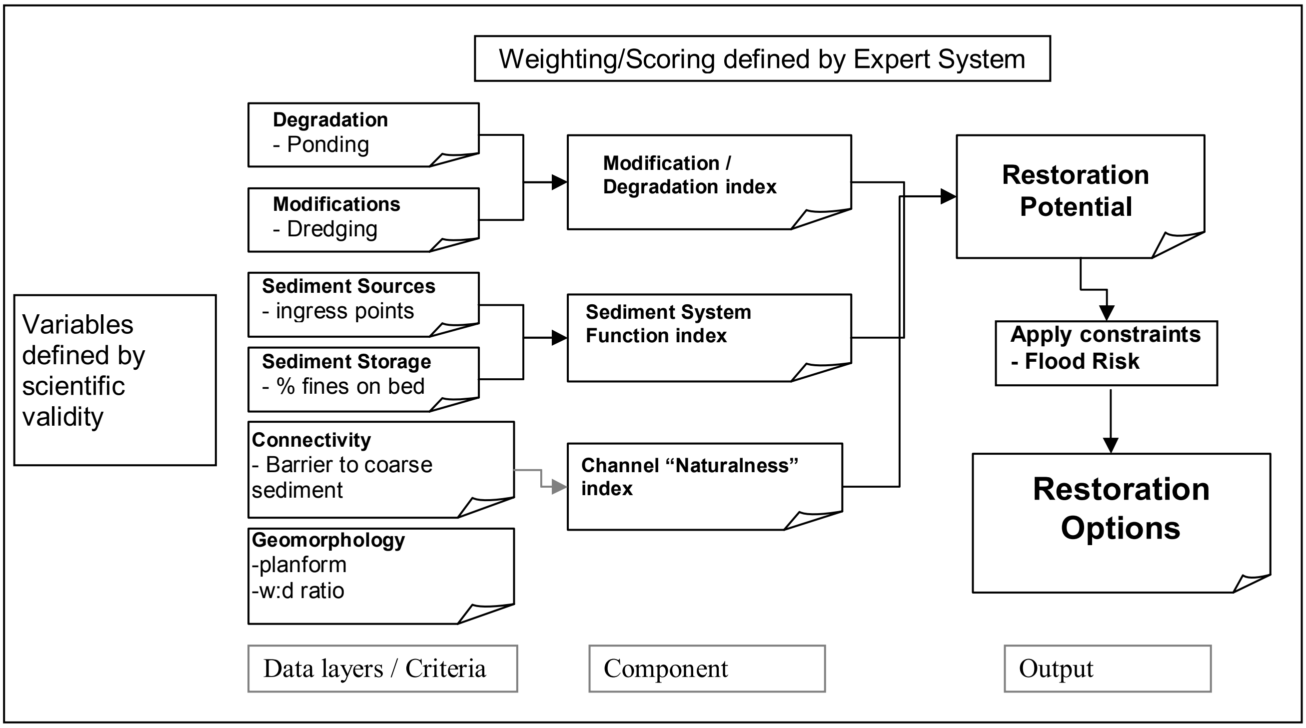


Figure 2.2 Multi-Criteria Assessment applied to River Wensum SAC using datasets derived from the fluvial audit.

3 Catchment characteristics

The River Wensum has a small catchment, but lies in a rural region with diverse and intense water management interests. It flows from west to east and joins the River Yare at Norwich. The landscape of the catchment is predominantly influenced by agriculture with intensive arable farming on the plateau and valley sides, whilst the floodplain is largely managed grazing marsh. The details of the Wensum catchment and river network are summarised in Table 3.1 and Figure 3.1.

Table 3.1 Summary of River Wensum catchment characteristics (Environment Agency 2001)

Attribute	**Value**
Catchment Area	593km^2
Stream Length	78km (study length includes 70.1km)
Relief/Slope	Catchment has very low relief with river bed elevation falling 60m over a drainage path of 73km (average gradient = 0.00082m/m).
Principal Tributaries	River Tat, Langor Drain, Guist Drain, Wendling Beck (Whitewater/Blackwater), Penny Spot Beck, Blackwater, Swannington Beck and River Tud.
Hydraulic controls	14 mill structures (South TF881282, Sculthorpe TF893303, Fakenham TF919293, Great Ryburgh TF964269, Guist TF997251, Bintree TF998243, Elmham TG003204, Swanton Morley TG021186, Elsing TG050177, Lyng TG072178, Lenwade TG102182, Taverham TG159137, Costessey TG177127, Hellesdon TG198105) including 3 long-term gauge stations at Fakenham (163km^2), Swanton Morley (390km^2) and Costessey (563km^2).
Hydrology	Flow is derived from groundwater base flow, direct surface run-off, and direct recharge to the river and drain network. The hydrological regime is that of a groundwater fed river, with base flow indices of 0.85 in the upper reaches to Fakenham and 0.7 at Costessey Mill. Water level management of the river and drain network significantly affects the levels and flows within the floodplain.
Geology	The solid geology of the whole area drained by the Wensum is Senonian (Upper Cretaceous) Chalk which dips gently north-eastwards at an angle of 1 to 2 degrees and is fine-grained, fissured limestone. However it is generally covered with drift (<10m thickness) - boulder clay on the higher plateau ground with glacial sands and gravels on the valley flanks. Chalk outcrops at the surface intermittently in the floodplain of the upper reaches of the Wensum and River Tat valley, and in the Wensum valley between Guist and Costessey.
Hydrogeology	The well-fissured chalk provides a major natural aquifer in addition to the storage of the permeable glacial sands and gravels which overlie the chalk.
Soils	Calcareous soils in upper catchment.
Land Use	Intensive arable land use dominates the landscape on the higher plateau ground and valley sides, although pasture, scrub, gravel pits, wetlands and scattered woodland remain on the floodplains.
SSSI	The River Wensum was designated in 1993 as a 'whole river' SSSI as one of the best examples of a naturally enriched calcareous lowland river. In terms of the Joint Nature Conservancy Council (JNCC) River Type classification, the upper river is characterised by JNCC River Type III 'Chalk rivers and other base rich rivers with stable flows', with transitions to Type I 'Lowland, low-gradient rivers' on the lower reaches upstream of Norwich. However, some river reaches currently support River Type communities that indicate varying degrees of modification e.g. IV 'base-rich/neutral impoverished rivers'. With regard to reaches that support Type II 'Lowland, clay-dominated rivers', these may be the product of modification and channel management. During the 2002 Macrophyte Survey (Grieve and others 2002) it was found that some of the lower reaches which had previously been recognised as Type Ic in 1980 (Holmes) had been degraded to Type IIc. A number of other SSSIs lie within the Wensum catchment, notably Sweetbriar Road Meadows (downstream of the downstream limit of the Wensum SSSI), Whitwell Common (on the Blackwater) and Dereham Rush Meadow, Dillington Carr and Beetley and Hoe Meadows on the Wendling Beck. In addition, there are a large number of County Wildlife Sites along the floodplain of the Wensum and tributaries. The Wensum valley is also included within the Broads Environmentally Sensitive Area.

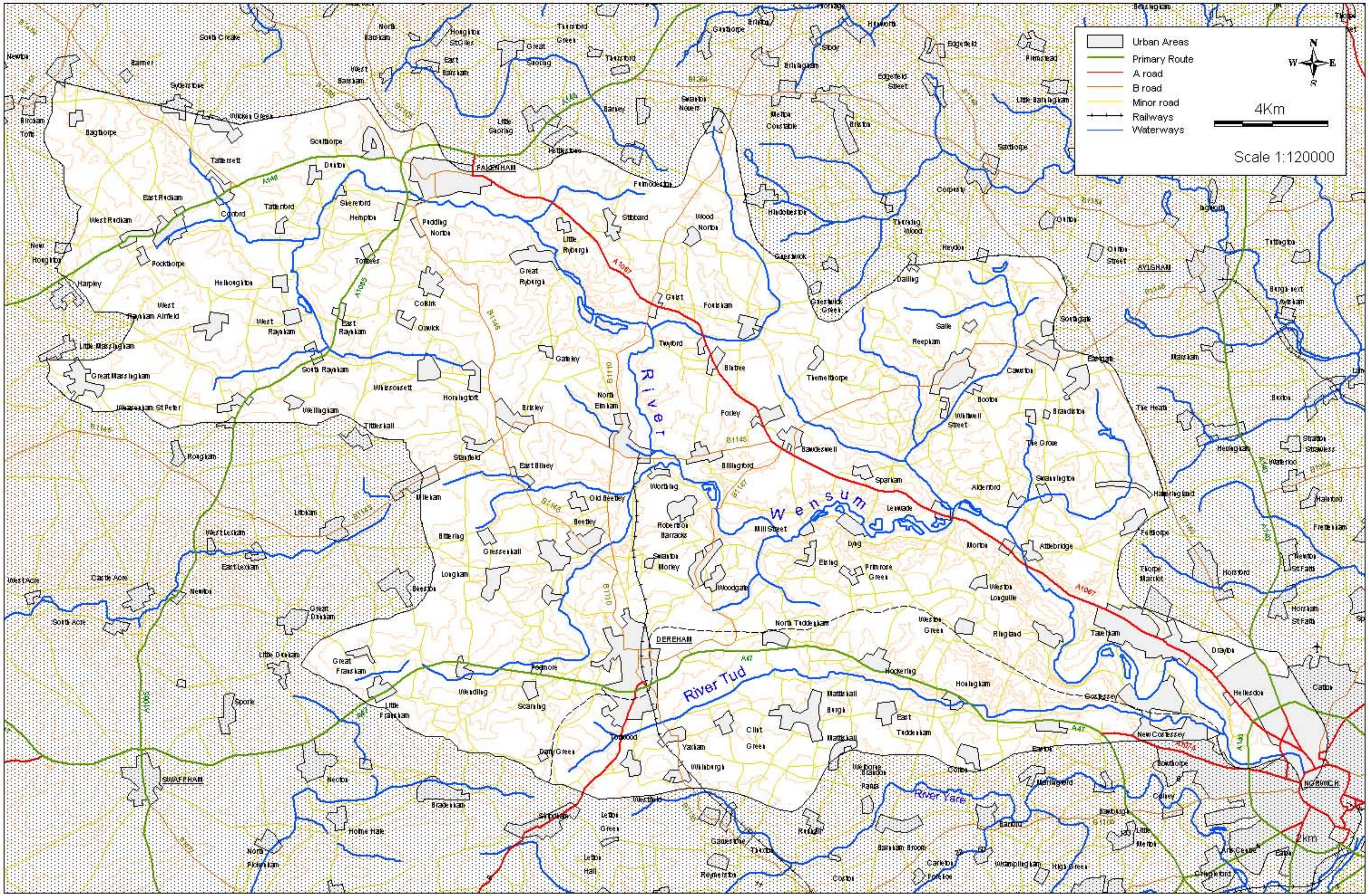


Figure 3.1 Catchment summary map of the River Wensum.

3.1 Geology, topography & soils

The River Wensum has an easterly draining catchment flowing over a mixed geology overlain by quaternary sediments of mixed origin. The evolution of the major landscape units in the Wensum valley relate primarily to two main periods of geomorphological activity; the Anglian glaciation (480-430k BP) that created the Fen basin, and the subsequent re-modelling of the Anglian glacial landscape by periglacial slope and fluvial processes during the Wolstonian glacial (300 – 130k BP) (Gibbard, 1991). The Anglian glaciation (Isotope stage 12) resulted in erosion of mudrock and chalk of the Fen Basin, and the deposition of chalky boulder clay over the area covering the upper Nar and Wensum catchments (Clayton, 2000). It is likely that many of the dry valley forms of the upper Nar and Wensum were formed under periglacial conditions during the Anglian and Wolstonian glacials. Slope processes and runoff characteristics of frozen ground are very different to temperate conditions associated with the current climatic regime. Furthermore, valley gradients were generally steeper since base-levels were lower (Gibbard & Lewin, 2003). Sediment evacuated from the valley slopes would have been transported and reworked under these conditions. Thus as climatic conditions ameliorated towards 130k BP, a phase of aggradation and incision driven by climatic fluctuations, created a suite of river terrace fragments within the Wensum valley utilising the available sediments derived from earlier slope activity.

The soil series within the Wensum catchment is strongly influenced by the complex geological history described above. It is essential for understanding the large scale controls on sediment supply from erosion of the land surface. Figure 3.2 depicts the relationship between the geology, topography and soil formation within the Wensum Catchment.

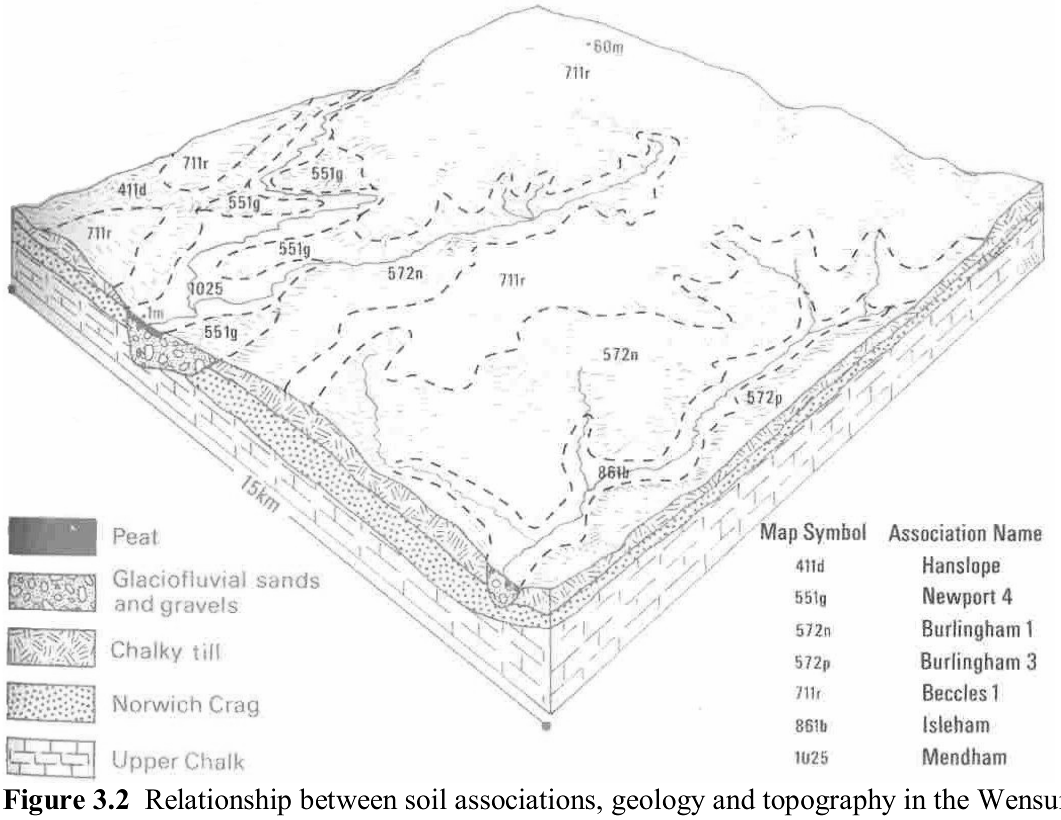


Figure 3.2 Relationship between soil associations, geology and topography in the Wensum catchment after Hodge and others (1984).

The Wensum catchment is characterised by rich loams, silts and sandy peats, which have a high potential for cultivation. The influence of soil types strongly affects the hydrological properties of the soils and river network. Although influenced by soil texture, permeability is determined largely by the underlying glacial deposits of clays, sands or gravels. The soils in the river valley are of low permeability where coarse loams overlie clay, while the highly permeable sandy loams on the valley slopes are highly fertile but require irrigation. The floodplain soils are dominated by soils of the Isleham 2 Association (861b) that are peaty sandy soils affected by groundwater. The floodplain between Alderford and Norwich are Adventurers' 2 Association (1024b) which are semi-amorphous peats, often overlying sandy subsoils.

In the headwaters, the soils are a mix of Barrow (581f) – deep well drained coarse loamy soils developed over clayey subsoils, and patches of Newport (551g) series – wind and water erodible sandy soils. This series is more extensive between Reepham and Norwich.

There is a clear correlation between topography, geology and soil erodibility that highlights the steeper valley sides and lighter sandy/sandy loam soils as sensitive to both water and wind erosion (Hodge and others1984). These authors highlight the need for careful management of the erodible soils of the area.

Figure 3.3 highlights those areas in the Wensum catchment with the most erodible soils, although other factors, such as slope, need to be assessed to establish the likelihood of sediment supply to the river. The lower reaches of the Wensum (downstream of Lenwade), the Blackwater from Reepham, Swannington Beck and the lower reaches of the Tud border particularly sandy soils. In the upper reaches of the Wensum, 'hotspots' of erodible soils occur south of Fakenham, at Doughton and around the headwaters of the Tat.

The topography of the Wensum catchment is relatively subdued with a maximum elevation above OD of 95m at Bradenham Hill south of Wendling (NGR: TF925105) giving a total topographic range of 85m. The primary topographic features are the valley of the River Wensum and its main tributaries the Wendling Beck and River Tud. These and minor tributaries dissect the eastward dipping Upper Chalk and overlying chalky boulder clays and fluvio-glacial sands and gravels that form the catchment surface. The land surface is further dissected by a network of dry valleys which extend into the catchment above the perennial stream head. There is no evidence that these are ephemeral channels but they are relics of the extended river network associated with spring sapping and runoff under periglacial process regimes and provide a focus for surface runoff (Environment Agency 2003).

Important controls on sediment transport are the channel gradient, and water surface gradient. Figure 3.4 presents a representation of the long profile of the River Wensum derived from topographic surveys (Environment Agency 2003) and extended to source using spot height data from the OS 1:25,000 Map. The water surface elevation is derived from ISIS hydrological model output for the 1:5yr flood (Environment Agency 2003). The mills that influence water levels and channel gradient are listed in Figure 3.4. The stepped profile of the river is clearly shown, with backup of flood water behind each of the mill structures. This backwatering is more extensive at low flows. The impact of the mills on bed elevations is typically to create a steeper section downstream of each mill, followed by a reduction in bed gradient immediately upstream. Thus the profile has been described as a series of ponded low gradient sections separated by short steeper sections. The headwaters upstream of the confluence with the River Tat are characterised by steeper bed gradients and an absence of mill structures.

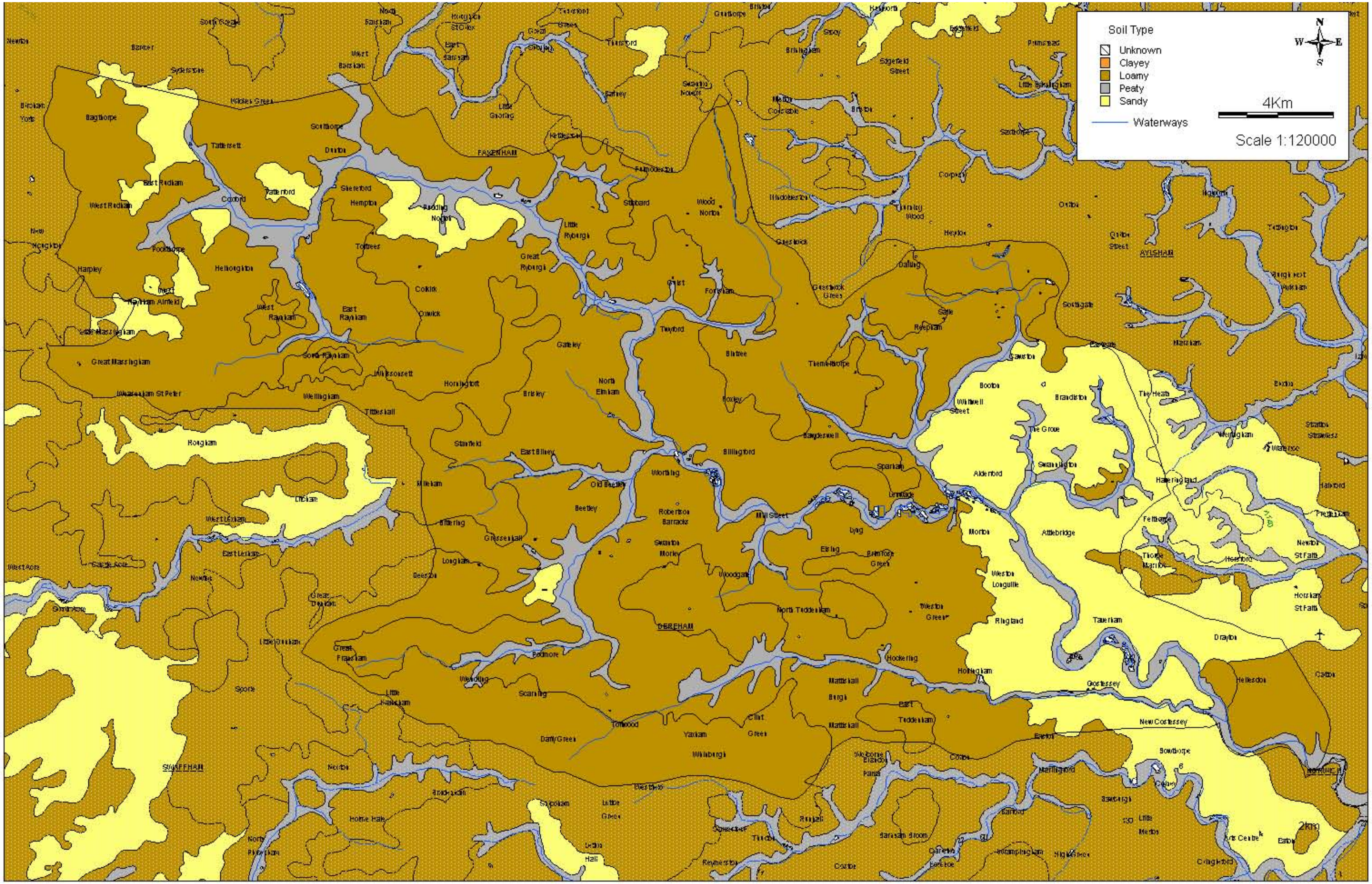


Figure 3.3 Soil erodibility in the River Wensum catchment.

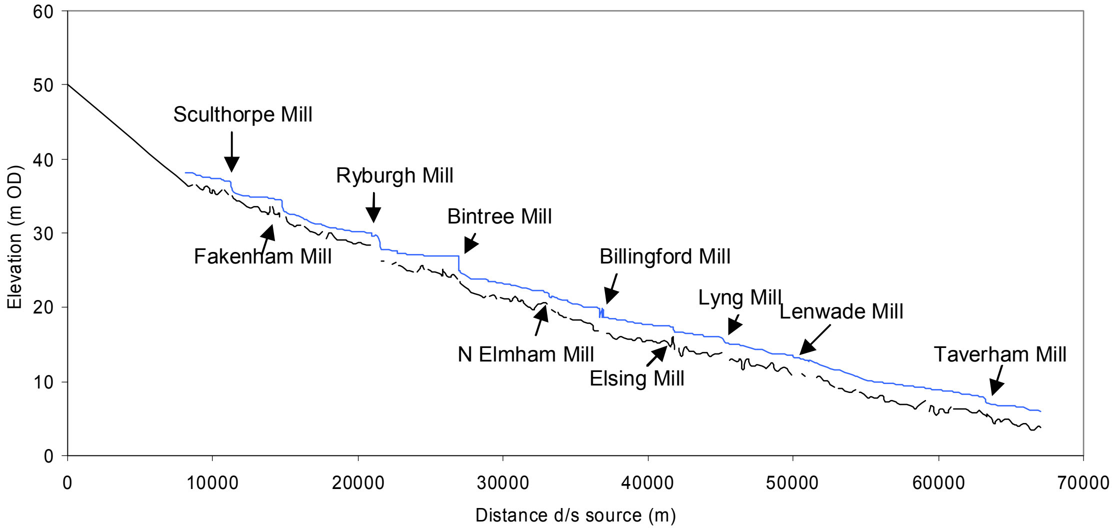


Figure 3.4 Long Profile of the River Wensum from source at Whissonsett to Costessey.

3.2 Hydrological characteristics

The River Wensum has a groundwater dominated flow regime, arising from the chalk aquifer, characterised by a high Base Flow Index (BFI) and a low index of flashiness (Figure 3.5). Chalk is a soft and highly porous rock, and the principal hydrological pathway to the river network is through slow percolation into the underlying aquifer and subsequent discharge via springs, which may occur at various points along the length of the river. The slow release of water from the aquifer greatly attenuates the sporadic nature of rainfall, providing a relatively stable hydrological regime with a characteristic annual cycle. At Fakenham the Wensum has a BFI of 0.82 (ie 82% of the flow is derived from the underlying aquifer); whilst further downstream at Costessey the BFI is 0.73. The flow regime is similar to other "classic" chalk rivers but as one progresses downstream, the moderating influence of the less permeable, overlying glacial deposits (boulder clay) become more evident.

The regime is modified by a series of hydrological controls including: water abstraction from the aquifer and surface waters, and effluent discharge from the aquifer and to the perennial channel network (Boar and others 1994); fourteen weirs which once provided the hydraulic head necessary to power the water mills; extension of the natural drainage network by field drainage systems; and modifications through gravity drainage and pumped drainage schemes. **The flow regime is therefore modified and not natural.**

The influence of groundwater leads to a flow regime typified by a progressive seasonal rise in water level within the channel, peaking in March and April (Figure 3.6). Aquifer recharge occurs in the previous autumn; hence low flows are a function of low autumn rainfall in the preceding year. Naturally, flooding of adjacent floodplain occurs during the high spring discharges. However, it should also be noted that although discharges to the river channel are at their lowest during the summer, the growth of aquatic macrophytes increases friction, and holds water levels at a higher level. In addition, the management of mills can also influence the hydrological regime of the river.

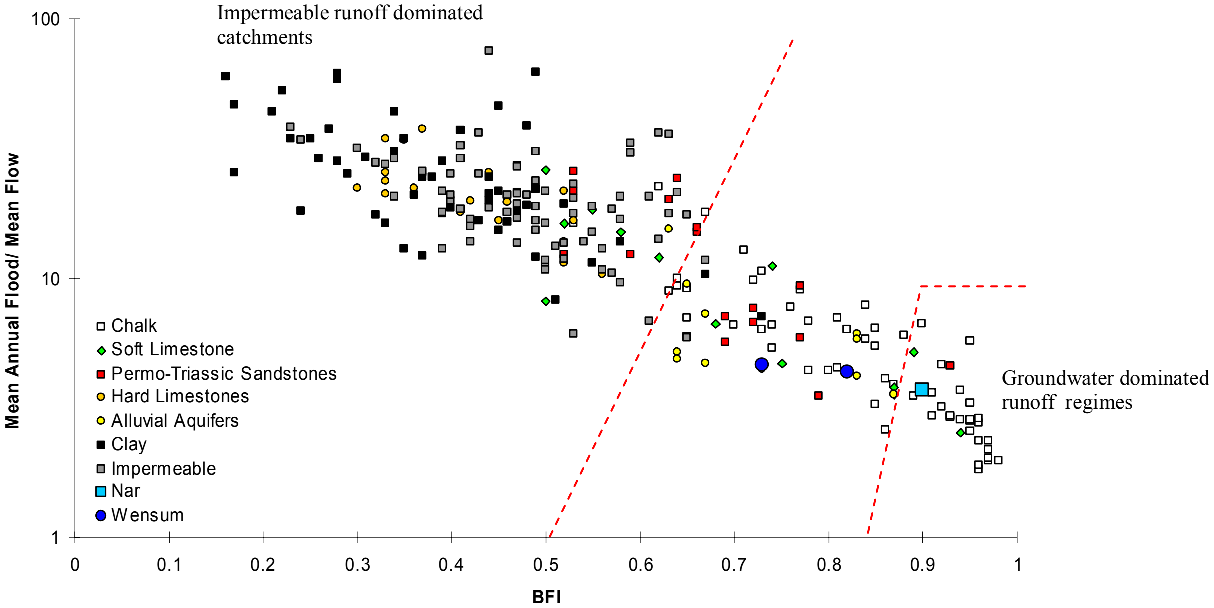


Figure 3.5 Groundwater dominated flow regime of the River Wensum is slightly moderated by overlying glacial deposits. "Pure" chalk river hydrology is characterised by a Base Flow Index (BFI) > 0.9. The lack of flashy hydrological response of the Wensum is evident from the low ratio of MAF/Mean Flow (after Sear and others 1999).

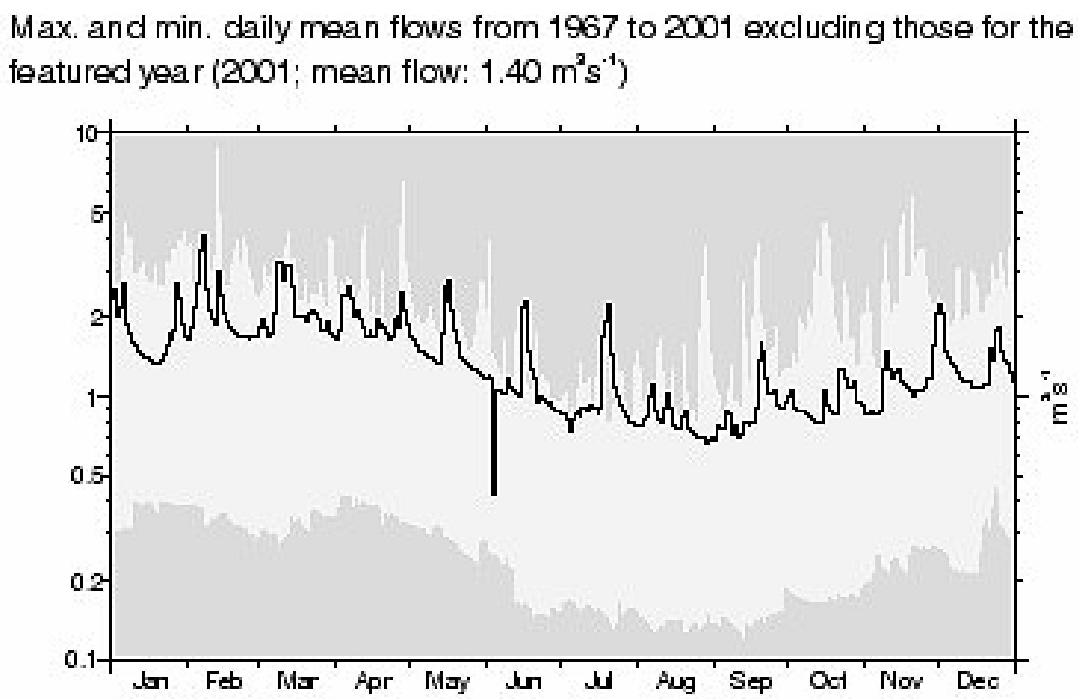


Figure 3.6 Average annual flow regime for the River Wensum at Fakenham Gauge Station. Source CEH National Water Archive

The creation of a series of gravel-pit lakes increases the surface area of water and the extent of evaporation losses to the system. It is unknown what these losses amount to, or whether flows are effluent or influent from these lakes to the river; it is understood that the hydrology and water quality issues on the Wensum are being considered separately.

There is no additional surface water available for summer abstraction, although there is the potential to abstract winter water for storage and subsequent use. The policy on abstraction has changed since 2000 with current policy not to issue any 'new' groundwater licences until the Habitats Directive review of consents process has been concluded and until the Broadland Rivers Catchment Abstraction Management Strategy (CAMS) has been finalised. The Environment Agency is considering on a case by case basis renewals of licences which have expiry dates attached. There are 348 licences for groundwater abstraction totalling 12995 thousand cubic metres per annum (tcma). There are 34 licences for surface water abstraction, totalling 17914 tcma. Anglian Water Services Ltd is by far the largest abstractor of both ground and surface water, accounting for 17009 tcma of the surface abstraction (13% of the average flow at Costessey gauging station), for public water supply. Public water supply abstraction within the catchment is to be investigated as part of the Water Authority’s Asset Management Plan 4(AMP4).

Boar and others (1994) found that land use changes in the catchment have not had a significant influence on either flow volume or flow regime since the flow record began in the early 1960s, and that there was no change in the baseflow component or in the seasonal distribution of runoff from the surface catchment. Abstraction, particularly spray irrigation during dry growing seasons, can significantly alter the flow volumes, for example, during the 1989-1992 drought maximum losses of 15% were incurred in the Wensum.

With the construction of water mills, in the nineteenth century, a stepped long profile was imposed on the River Wensum and today, fourteen weirs interrupt the natural gradient of the Wensum. These result in the creation of long, deep impounded sections upstream of the structures and short, steep riffle-run sections downstream. Although milling did not alter flow volumes, the channel geometry was altered significantly (damming, widening, bed lowering, straightening and redirecting) which in turn affected flow velocity, water depth and sediment transport processes. Despite the decline and end of milling by the early 1960s, the weirs are still in place, but the inherent management of flows through the system appears to have been long forgotten. The reduced sediment transport since the end of milling, in association with increased external loadings of sediment from changes in land use, have led to the deposition of silts over an increased proportion of main channel (Boar and others 1994). As the depth of sediment increases in impounded reaches, this results in a marginally greater gradient on these reaches, thereby tending to increase the influence of impoundments even further upstream.

Water quality issues are detailed in several reports (eg Boar and others 1994), but of relevance to this geomorphological study is the evidence of runoff from the catchment surface associated with agricultural activity that is considered to be a contributory factor in relation to the enhanced nutrient levels in much of the river network. Phosphorous levels increased markedly from 1975 and were associated with effluent from Sewage Treatment Works. Siltation in the impounded reaches upstream of the weirs provides a ‘sink’ for the phosphates, which has implications for the remobilisation of these deposits in that the phosphate may be released. Phosphate stripping has been put in place at Fakenham and Dereham sewage treatment works (STWs) under AMP3 and will be implemented at a further seven smaller STWs under AMP4. Phosphate stripping has also been installed at the Bernard Matthews poultry processing factory at Great Witchingham. Given the high level of phosphate stored in impounded river reaches, there could be benefits in removing the silt from some of the more heavily silted impounded river reaches immediately prior to restoration. This would avoid remobilising of large quantities of silt, but would also avoid the trapping of silt in fresh gravels when carrying out work to restore gravel beds.

A proportion of the elevated phosphorous levels are derived from agricultural runoff, and this is cited as circumstantial evidence for connectivity between the land surface and the river channel (Boar and others 1994).

There are three current, vital contributions to the hydrological understanding and river management of the Wensum, the Water Level Management Plan (WLMP), the Broadland Rivers Catchment Abstraction Management Strategy (CAMS) and the Broadland Rivers Catchment Flood Management Plan (CFMP). The WLMP is extant (Environment Agency, 1999) but due to be reviewed in 2006, whilst the CAMP is under development (Environment Agency, 2001) and the CFMP has been given foundation by the Upper River Wensum Strategy Study (Babtie, Brown and Root, 2003).

These procedures bring together huge amounts of relevant data and there is little point in listing it again. Each of these confirms that the dominant influence on the behaviour of the Wensum is the combination (harmonious balance) of climate controls and traditional management practices: *inter alia* flood protection, channel maintenance, water abstractions/discharges.

The WLMP, by its nature, emphasizes the relationship between channel, riparian and floodplain hydrological regimes, eg 'If any changes to the water levels regimes are proposed the full implications of such changes on both agriculture and the environment, and in particular the special character of the grazing marshes, must be fully considered' (p. 5).

However, the WLMP does not limit its scope to water levels, but also considering geomorphological issues such as silt and states:

'The build up of silt deposits, whether on the riverbed or the margins, is most apparent in 10 of the 14 river reaches'…..'It has been noted that the riverbed between Costessey Mill and Hellesdon Mill is covered in a deep layer of muddy silt'……..'Sources of silt should therefore be identified, to enable the definition of risk areas and thus the priority sites for silt removal'. (p. 15).

Of greatest relevance to the present study is what is described in the WLMP as one of the 'few unresolved differences' between the parties. Debate should be engaged between 'permitting or engineering the channel to become more narrow and sinuous' and restoring 'former conditions through reducing silt input and reinstating the old flow regime, mimicking former milling practice' (p. 18). In terms of creating a supportive agricultural environment for river enhancements (the WLMP advocates a 'natural' riffle-pool sequence) the Plan calls for extended uptake of the ESA scheme in the floodplain (MAFF, 1997).

The Wensum CFMP needs to recognise the results of the hydraulic modelling exercises now carried out for both the Norwich area and the Upper Wensum (Jeremy Ben Associates, 2001; Babtie, Root and Brown, 2003). The context of this activity has been set by:

- Significant public and political interest in flooding since Easter 1998, the 'Millennium Floods' and new legislation – the Water Framework Directive).
- Advances in our understanding of the role of floodplains and in technical measures to map their relief.
- The introduction of a significant social science contribution to flood risk management, including roles for economists, planners and insurers.

One is encouraged to consider flooding as resulting from out-of-bank flows in major rivers (ie the Wensum main-stem) but this is not the view of insurers who report losses incurred by for example, drains blocked by leaves or sewers backing up. One is not questioning the modelling focus of the Wensum studies but in the modern context of flood risk management the actual cause of each inundation event in-house or on-farm is essential information. There is a continued role for flood modelling on the Wensum because of the sensitivities introduced by the natural regime; the river has a very 'flat' flood frequency curve meaning that choice of a protection standard is vital but very uncertain. In everyday terms, the groundwater controls and low intensity of rainfall on the Wensum catchment (under current climate conditions) mean that the impacts of rare floods (in terms of those affected) are not that exaggerated compared with the flood levels occurring every couple of years. This is the hydrological characteristic that is vital to our understanding of the Wensum, especially through the slowly-evolving local compromises between 'hard' flood protection and regular channel maintenance. Babtie, Brown and Root (2003) put it as follows (in terms of SSSI and SAC):

'The existing river maintenance regime is essential in order to retain many of these designations'

Modern flood risk management is tougher than before – local compromises are considered invalid if they depended merely on local politics (through Land Drainage Committees) and the cost-benefit approach has been considerably refined (whilst not yet including serious amounts of natural capital).

The Upper Wensum study is very broad in the scope of options considered for future flood protection. Its prognostication on climate change accepts official advice that flood peak discharges are likely to increase by 20% in the next 50 years.

Unfortunately, one of the common strategic remedies advocated by geomorphologists and conservationists alike – upper catchment floodplain storage for flood waters – does not emerge as an adequate remedy to achieve desirable standards of service in the Wensum – there is simply not enough floodable land (unless a planning approach changes the land-use map considerably) to offer downstream protection. The same flood storage inadequacy is also an outcome for abandoned mineral excavations.

In fact, improved flood warning may be the optimum system-scale management approach, being in tune with good flood risk management and avoiding huge structural 'hard' flood protection measures. The extra gauging will also provide an excellent basis for eg monitoring of physical and chemical changes in the river; and a spread of gauging to prominent tributaries would be an additional benefit.

Now that model frameworks are established for the Wensum they must be updated and improved as the policy compromises rise to new sophistication, eg in the CFMP. If natural capital issues become properly costed, the very few at-risk properties and infrastructures considered by the Upper Wensum strategy (cf. other similar lowland catchments) might find their standard of protection (set at a very broad range of 5-50 years) declines. It is currently set at circa 13 years for some properties in Lyng and circa 20 years for some at Fakenham.

Planning authorities also have highly relevant planning powers in relation to ancient mills eg change of use, and cannot now be excluded from flood risk management. Babtie also report negatively on planning permissions granted within the indicative floodplain mapping area (albeit the revised one); given the possible changes under climate shifts this must be fixed – the delicate balance is perhaps not evolving after all.

The Upper Wensum modelling exercise has suggested ‘local containment’, via new cut-off walls as an optimum flood risk management strategy, making full appraisal of the environmental constraints, for threatened properties (mapped) in Fakenham, Worthing, Lyng and Lenwade.

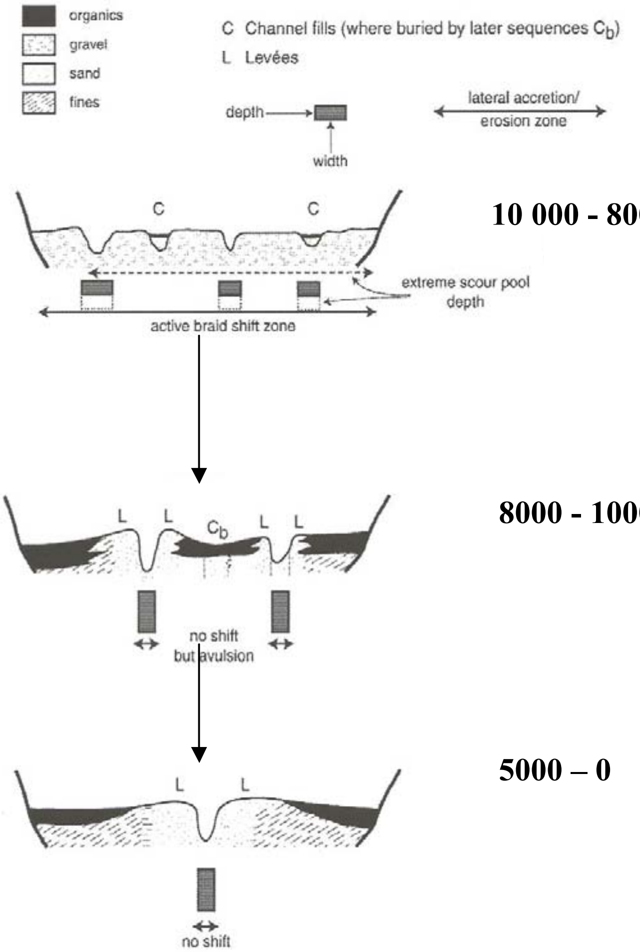
It is interesting to note that Babtie consider that ‘the aquatic weed community in the River Wensum is a primary reason for the designation as a SAC’ (Vol. 1: p. 16). Later the report lists the two targets for dealing with flood defence within the Conservation Strategy for the River Wensum SSSI:

- Ensure that flood defence works have a neutral effect on the conservation interest of the river and that wherever possible opportunities are taken to enhance this interest.
- Allow river processes to continue uninterrupted unless there are negative flood defence or conservation implications. (Vol. 1: p. 17).

The reference in the report to “allowing river processes to continue uninterrupted unless….” reflects the fact that the need for protection of people and property is sometimes a constraint on allowing natural river processes to continue. Similarly, restoration of natural river processes may have adverse impacts on the existing biodiversity of floodplain habitats.

3.3 Geomorphological processes & catchment evolution

Section 3.1 detailed the development of the main geological and topographic features of the Wensum catchment. In this section we focus on the more recent processes and specifically the evolution of the valley floor and river channel. The next main phase of landscape evolution occurred during the past 10,000 years of the Flandrian. This period is characterised by a sequence of valley floor alluviation and incision creating the most recent fluvial terraces in the Wensum valley. The specific conditions in the valley floor are unknown and require investigation. However the sequence of valley floor alluviation developed from other lowland river systems suggests that phases of climatic deterioration and amelioration result in phases of valley alluviation and incision. During the early Holocene, the river channel metamorphoses from an inherited braided river system dominated by higher energy gravel/sand associated with periglacial conditions with higher runoff, to multiple channel anastomosed rivers confined by cohesive floodplain fills and woodland. Subsequent mobilisation of fine sediments by forest clearance (typically from c.5000 BP) of the catchment and valley sides results in blocking of multiple channels with fine sediment and the creation of the stable, single-threaded meandering channels occupying the present river course (Brown, 2002). This sequence is considered to be analogous to those of the interglacial; hence the sequence of valley fills within lowland river valleys tends to be complex (Gibbard & Lewin, 2003). The channel sequence most likely to have occurred within the Wensum valley is demonstrated in Figure 3.7.



Braided River
Dynamic gravel-sand bars and channels migrating over valley floor.

10 000 - 8000 BP

Anastomosed River
Stable multiple channels confined by cohesive fine sediments and floodplain forest. Peat development

8000 - 1000 BP

Meandering River
Stable single channel confined by cohesive fine sediments and floodplain forest. Peat development.

5000 – 0

Figure 3.7 Holocene floodplain and channel evolution of the upper Wensum. A conceptual model based on Gibbard & Lewin (2003).

The sinuous course of the Wensum follows a large valley meander, which was created by the much greater discharges conveyed in the glacial melt water channels. Today, the Wensum drains a small, lowland catchment with a maximum elevation of less than 100m OD. The natural low gradient (0.6m/km), exacerbated by the engineering for water milling and drainage, and significantly reduced discharge, has resulted in an ‘under fit’ channel (Richards 1982), inactive in terms of channel migration.

The River Wensum can therefore be seen in a natural condition to be divided up into distinct hydro-geomorphological types, each of which would support different physical habitats and associated biotic communities. Table 3.2 details the broad semi-natural geomorphological reach types existing within the Wensum catchment. These are visualised in Figure 3.8. Channel management within these types has created a suite of reaches with more or less modification from the semi-natural conditions.

Table 3.2 Geological/hydrological/topographically determined zones along the River Wensum.

Types	Extent	Ref. Condition geomorphology & habitat
0	Throughout the main catchment	Dry valley network with spring sapped headwalls. No historically recorded flow but overland flow and natural pathways for runoff possible. Underlying sediment a mixture of colluvial slope wash and re-worked channel lag deposits.
1	Headwater – Pear Tree Corner to Lenwade	Sinuous single-thread channel system with mixed surface and groundwater dominated hydrology. Strong coupling of channel and floodplain leading to wet marsh/woodland/fen community with peat development.
2	Lenwade to Hellesdon	Sinuous meandering channel formerly multi-threaded with woody debris and limited development of pool-riffle sequence. Groundwater dominated hydrology with extensive wet fen/Carr floodplain communities underlain by peat. Upwelling groundwater creates mosaic of wetland habitats including pools on floodplain surface.

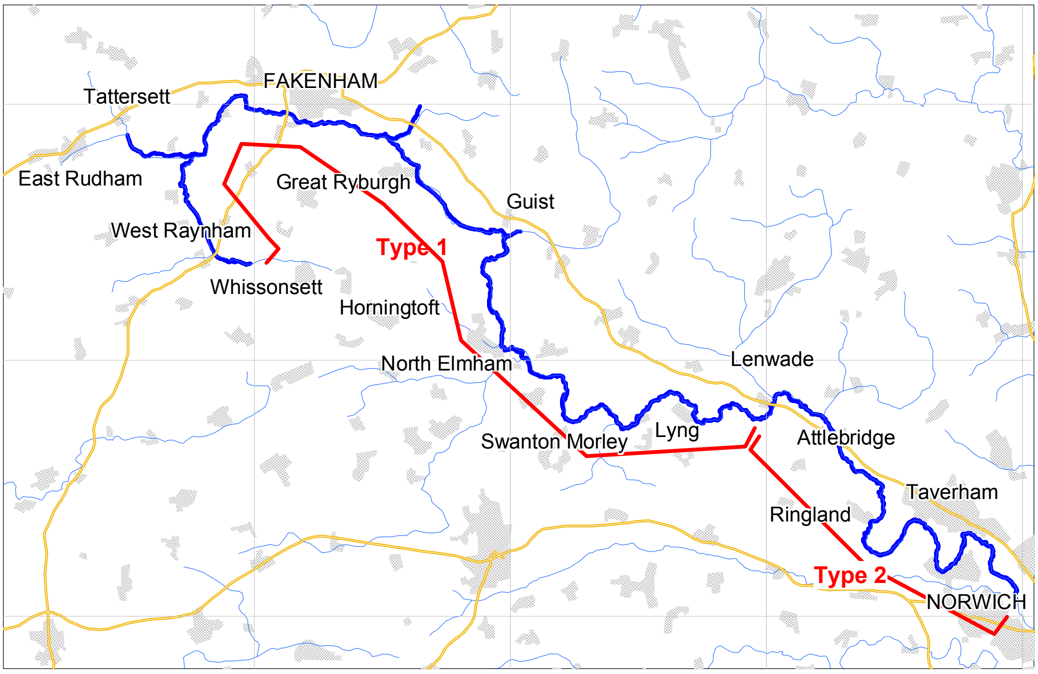


Figure 3.8 Typology of river channel geomorphology for the River Wensum and tributaries. Boundaries are speculative. © Crown Copyright. Data derived from OS 1:250,000 mapping EN 1000017954.

3.4 Catchment summary

The Wensum catchment is prone to production of sands and fine silts as a result of its glacial and periglacial history. It is a groundwater dominated hydrology with a relative absence of high energy floods. A relatively subdued relief creates low gradients throughout the river that, coupled with the low discharges associated with the groundwater hydrology, result in a low energy river sediment system. Thus the current river channel network and major controls on processes are seen to be the result of past processes. Contemporary channel management and land use management have subsequently modified the hydrology, sediment production and channel morphology.

4 Contemporary catchment management

The management of the River Wensum is influenced by the land use and land management of the catchment surface and floodplain as well as the modifications made to the channel over time. This section of the report details the main types of land use in so far as they influence the main drivers of channel geomorphology, sediment flux and water discharge (See Section 1.2). The section also chronicles the major physical modifications made to the river channel in so far as they influence the channel morphology and sediment transport regime.

4.1 Catchment land use and management

Catchment land use is known to contribute to the production and delivery of water sediment and nutrients from the land surface into the river network. Furthermore since over 90% of a river catchment is the land surface, the management and use of this surface strongly influences the nature of the river channel. In turn, the land use and land management is strongly controlled by the soil type, topography and climatic regime of the catchment. The catchment is now dominated by arable farming. Typically the well drained loamy-sandy soils of the upper catchment and valley slopes have been intensively farmed for arable crops and livestock, and more recently pig units. In the wet valley bottoms, low intensity grazing has dominated and scattered woodland remains. There is evidence, largely from the tithe apportionments, of considerable areas of grazing marsh bordering the Wensum (at least at Costessey in the mid nineteenth Century) as well as extensive other wetland features of osier and alder carr (Barley 2002).

Figure 4.1 demonstrates the land use classes for the Wensum catchment in the 1930's. The main differences compared with the present catchment are:

- 25% loss of floodplain grazing marsh in river corridor 1930-1994 (Boar and others 1994).
- 40% increase in surface drainage network since 1904 (Boar and others 1994).
- From the 1940s onwards, an intensive programme of land drainage started in 1940s to expand cultivation in response to the demands of the Second World War. Expansion and intensification of arable farming in the catchment ensued.
- Consequent decrease in the areas of permanent grassland and heath.
- Increase in gravel and sand extraction along the Wensum valley, which are then flooded and constitute deep water reservoirs.
- Increase in free range pig units on sandy soils.
- Expansion of urban land use around Norwich, Dereham and Fakenham and infrastructure development associated with road improvements.

Figure 4.1 Land use in the River Wensum in the 1930's (Data: Dudley Stamp land use survey of 1932).

Land use along the river corridor of the Wensum has remained at relatively low intensity, due to poor agricultural quality (low permeability) of the clayey valley soils and risk of flooding. Approximately 29% of the river corridor is arable (concentrated in the upper reaches), 53% meadow, 16% woodland and 2% urban (Boar and others 1994), creating a mosaic of wet meadows, improved and semi-improved grasslands, secondary growth wet woodland, and lakes.

4.2 River use and modification

An important element of any fluvial audit is the historical analysis of channel characteristics and change (Sear and others 2004, Sear and others 1995). These typically involve the use of cartographic data (maps), long and cross-section surveys, historical documents relating to river management and photographs. Key information derived from these sources includes:

- River planform and associated changes due to natural or human activity.
- Bankfull channel width and low flow width together with natural or human induced changes.
- Large sediment deposits (gravel shoals and mud banks) and fords.
- Channel and floodplain structures past and present (eg water meadows, weirs).
- Location of past channels.
- Channel dimensions and slope at bankfull or other water levels.
- Broad vegetation classes in the riparian zone and floodplain.
- Details and location of past river management.

The fluvial audit attempts to link these changes to the field observations and through this process enables interpretation and the development of an understanding of the current river form and habitat; in particular assessing the extent to which what is present today results from human modification or natural processes.

Assessment of the historic channel change has been conducted using maps dating back to the 1200s, OS 1st Edition maps 1:10560, OS Landline and aerial photographs (Table 4.1).

Table 4.1 Spatial Data sets describing the position of the Wensum.

Documents	1200s	1797	1898	2000
Maps	Parish boundary recorded on OS maps	Faden's map of Norfolk	OS County Series First Edition	OS Land Line
Aerial Photographs				**2000** Useful for corroborating land use

As a result of the natural low gradient, and long history of flow impoundment, in the Wensum has a relatively inactive geomorphology, with the exception of the transport of the finest substrates (silt/fine sands). As such any planform changes apparent from the comparison of historic maps are most likely to be a result of engineering, rather than natural processes.

The course of the Wensum has changed very little since the thirteenth Century (Boar and others 1994). The main planform changes between the 1200's and 1797 were at mill sites (Sculthorpe, Fakenham, Great Ryburgh, Elsing, Lyng and Lenwade) where the course of the Wensum was shortened by abandoning large meander loops. Between 1797 and 1898 a major deviation was engineered near Tatterford (related to Southmill) and the channel was straightened from Tatterford to Sculthorpe, with a major diversion upstream of Fakenham in Sculthorpe Fen for the three mills downstream. Additional channel straightening at Little Ryburgh, Great Ryburgh, Sennowe Hall, North Elmham and near Billingford Common may also have been for flood alleviation reasons. Many minor planform changes have occurred during the twentieth century (small meanders have been removed at Sculthorpe Fen, Great Ryburgh Common, Great Ryburgh Carr, downstream of Bintree Mill, upstream of North Elmham and near Attlebridge, Ringland and Drayton) in response to a policy of intensive land drainage and dredging after the Second World War (1953-57). Locations of significant changes in the channel from the comparison of the First Edition 1:10,560 with the modern map are illustrated in Figure 4.2. The full comparative maps are held within the GIS data.

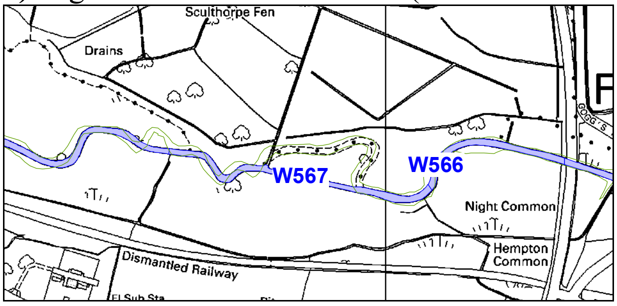
Since the decline of milling in the early 1960s, the artificially enlarged (widened and deepened) mill ponds upstream of the weirs have naturally accreted and are becoming increasingly narrow and shallow. In other locations not connected with mills, where land drainage created over deepened, and over widened channels (eg Ringland), channel narrowing is also occurring as the river attempts to attain an equilibrium form. This has also been observed in low gradient channels such as the River Windrush (Atkins, 2000) and the River Ock in Oxfordshire (Downs and others 1998) and is a common response to over-widening or increased depth through dredging.

Modifications to the River Wensum have been undertaken over much of the length of the river for over 1000 years. Modifications within the Wensum catchment take the form of:

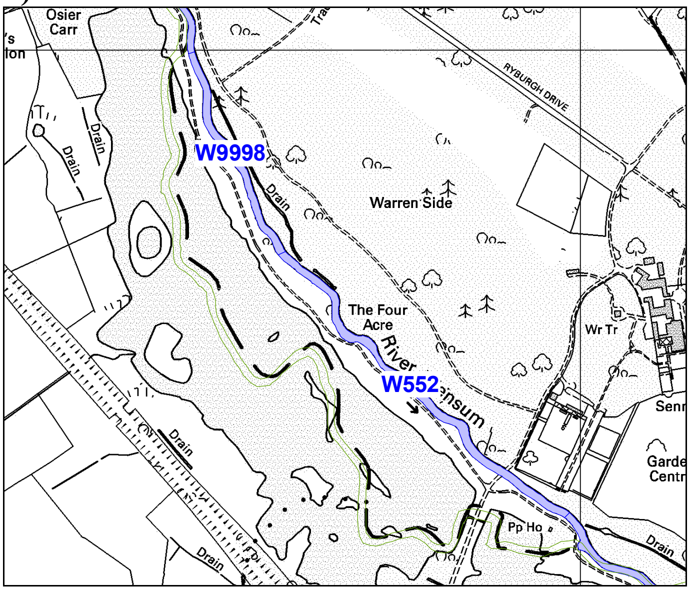
- Physical alteration to the course and dimensions of the river channel (eg straightening, widening).
- Changes in the connectivity between the river and the floodplain (eg embanking, water meadows).
- Removal of the bed substrate – consolidated bed material and deposited fine sediment (eg gravel removal / dredging (removal of consolidated bed material) and desilting (removal of fine sediment).
- Control of aquatic and riparian vegetation.
- Alterations to the water levels within the channel and downstream movement of sediment (mill weirs, sluices).

The floodplain of the Wensum has been extensively modified by the creation of a network of drainage channels. These drainage channel networks extend over the Wensum floodplain and can run parallel with the river for several kilometres. Drainage channels take water from the valley margins and floodplain, particularly adjacent to impounded river reaches where water levels are above the level of the land, and drain via gravity into the main River Wensum, immediately downstream of the impounding mill weir. The functionality of the floodplain drainage system is therefore linked to the stepped profile of the main river.

a) Night Common reach W567 (now reconnected by the Environment Agency),



b) Warren Side reach W9998 and W552



c) Lenwade W1082 and W1083.

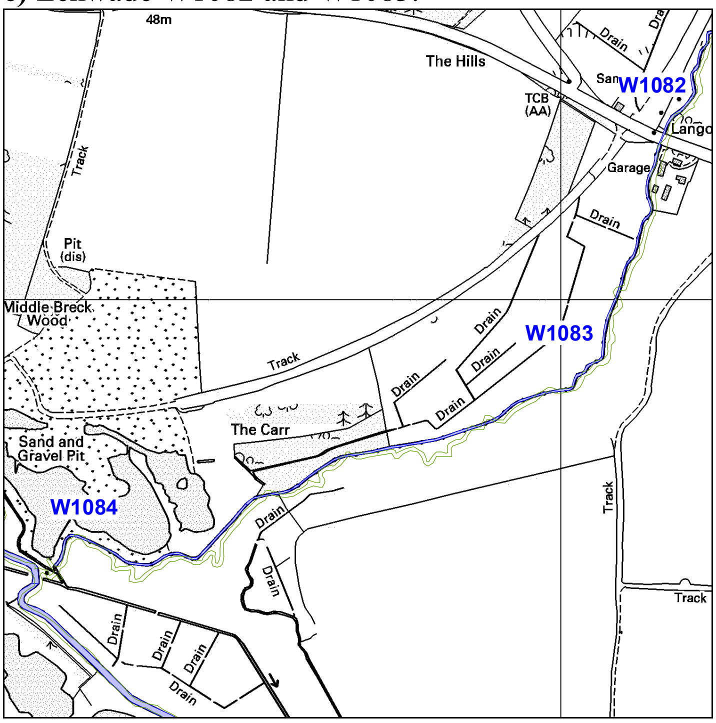


Figure 4.2 Illustrative locations of historic change mapped from the OS First Edition County Series maps. © Crown Copyright. Data derived from OS 1:10,000 mapping EN 1000017954.

In addition to these existing channel modifications, there are continuous rolling programmes of channel maintenance undertaken by the Wensum IDB (part of the King's Lynn Consortium of Internal Drainage Boards), both in the Wensum upstream of the confluence of the River Tat, and also in the network of gravity and pumped drainage channels in the lower Wensum. The Wensum catchment is almost exclusively drained by gravity, with only one small area drained by pump.

Further programmes of maintenance are undertaken by the Environment Agency on the 'Main River' section of the River Wensum and its tributaries, to manage the flood-risk to people and property. These take the form of desilting operations and an annual programme of weed cutting. Some tree and scrub management is also carried out.

The main periods and types of modification are listed in Table 4.2. These are not comprehensive but illustrate the extent and type of modifications made to the River Wensum. Further details of the modifications are contained in the GIS database and maps accompanying this report. What is important to recognise is that the Wensum, although following an old course, has been modified and continues to be maintained in a modified condition that subdues the action of natural processes within the reach. A long history of channel and floodplain management has resulted in a substantial proportion of reaches being modified to improve drainage or for milling. Thus although the river is widely recognised as a good example of chalk river, it is in fact largely modified.

Table 4.2 Channel modifications recorded on the River Wensum (Brookes, 1983) and Environment Agency /Kings Lynn Consortium of IDB updates, and maintenance records (Boar and others 1994).

Type of channel modification	Date	Type
Hempton	Pre 1950s	River raised above level of floodplain, creating large areas of marsh in which a new drainage network ran parallel with the river channel and re-entered the Wensum below the weir.
Fakenham, Costessey and Ryburgh Mills	Pre 1950s	Extensive drainage networks throughout the floodplain. Dredging and wooden hoarding required to maintain new, shortened planform of the Wensum.
Wensum - general (Shereford to Sennowe Park)	1953-57	Extensive dredging (5 mile stretch drag-line dredged)
Wensum – general	1950s/60s	Extensive weed cutting
Wensum – general	1970s	30km of river dredged each year
Wensum – general	1980/91	70km + dredged/year (including drains)
Wensum – general	1983-87	Grants for river maintenance reduced from 75% to 35% = reduced dredging and weed cutting.
Wensum – general	1988/89	Grants increased to 45% and establishment of National Rivers Authority created new period of maintenance activity but with emphasis on flood defence (with ecological constraints) rather than land drainage (with financial constraints).

To determine the level of modification along the Wensum, a multi-criteria assessment was carried out using all available data on channel modifications. First the modification data was digitised and mapped within the GIS. This included information on past modifications (eg navigation, mills, lakes) and current maintenance operations (eg data from the IDB GIS database). Each modification was classified in terms of the severity of impact on the channel and then the total number of modifications for a reach was summed to provide a modification level (1-5 where 1 = least modified and 5 = artificial). Out of a total of 120 geomorphologically defined reaches, only 23 did not demonstrate any **documented** signs or minor modification. This was reduced to 11 after cross-referencing with photographs of the reach giving a total of 15.9 km or 21% of the total river length surveyed including the River Tat, Guist Drain and Langor Drain. At total of 18.9% of the Wensum is not documented as being modified. The least modified reaches are found on the reaches between Lenwade Mill and Attlebridge Hall, and also on the reaches downstream of Taverham Mill.

In summary, the River Wensum is a modified watercourse with the least modified reaches in the upper catchment. Although not documented as modified, it is unlikely, given the association with mills and drainage networks in the floodplain, that those reaches identified as un-modified have not been modified at some point in time. However it is reasonable to suppose that in these cases modifications were undertaken earlier and therefore may have had time to recover to a more natural channel form. All other channel types are modified with most in the low-moderate level of modification. The status of the channel is therefore largely in less than favourable condition with regards to morphology and physical processes.

Specific influence of mills

This report has corroborated earlier reports that identified the presence of mill structures and associated channel modifications as the most significant morphological impact on the River Wensum. The impact of milling may be summarised as follows:

1) Re-location of the river to the floodplain boundary to increase hydraulic head or straightening of the channel to provide hydraulic head (eg Tatterford (Southmill), Hempton Fen (Goggs Mill), Sculthorpe Mill, Fakenham (Dewing & Kersley Mill), Ryburgh, Elsing, Lyng, Lenwade & Costessey Mill).
2) Channel deepening and widening to create a mill pond for water storage (3-10m increase in width and up to 3m depth – Boar and others 1994).
3) Modification of low-flood flow hydraulics and water levels due to presence of weir in a low gradient river, creation of ponded and still water physical habitats typically affecting 1-2km upstream (Environment Agency 2003).
4) Barrier effect on sediment transport from upstream leading to accumulation of fine sediment in mill ponds and ponded sections.
5) Creation of localised scour pools and steeper gradient reaches immediately downstream of mill weirs.
6) Modification to floodplain water tables resulting from perched or elevated water levels (the effect is likely to vary according to whether the channel has been moved to the floodplain margin or simply embanked and straightened.
7) Long term accumulation of nutrients (P) and organic matter within the mill ponded reaches and increased retention time – nutrient spiralling is lengthened.
8) Creation of a network of floodplain drainage channels that take advantage of the head loss provided by the mill structures (Boar and others 1994, report a 40% increase in the drainage channel network since 1904 with most of it in the floodplain).

The decline in mill working over the twentieth century has resulted in two main responses:

1) Removal or modification of the operation of the mill structure followed by narrowing and silting of the disused upstream mill impounded reach and adjustment of channel dimensions back to more 'natural' channel width (eg Goggs Mill, Dewing & Kersleys Mill, North Elmham, Lenwade, Taverham (Boar and others 1994)).

2) Maintenance of mill structure with fixed water level leading to slight adjustment (reduction) to maintained channel width, silt accumulation on the river bed and presence of extensive upstream ponded reaches.

The impact of the staircase of mills along the Wensum is a series of discontinuities in channel form, sediment and associated nutrient fluxes, organic and nutrient processing, lateral exchange with the floodplain and barriers for instream biota. The creation of essentially still water habitat over a significant proportion of the river length has changed the ecology of the channel. The River Wensum is therefore a fragmented channel with a higher than natural capacity for accumulation of fine sediment. It should be recognised that the mill structures and influence of milling is in places over 900 years old. However, the milling regime is different today than it was up to the *c.* twentieth century. In the past, mills were often left open during higher flows, whereas the current regime typically retains upstream water levels. The difference in the post-milling era is that mill ponds are normally kept full at all times, and that the daily fluctuations in water level (including downstream flushing of fine sediment) no longer takes place.

4.3 River conservation status

The whole of the River Wensum from Peartree Conrer at Whissonsett to Hellesdon Mill is designated a Special Area of Conservation (SAC) based on its support for several Annexe II species (see section 1) and an Annex 1 habitat.

In addition the floodplain of the Wensum and Wendling Beck includes four SSSI wetland sites: Beetley and Hoe Meadows SSSI, Potter and Scarning Fens SSSI, Dereham Rush Meadows SSSI, and Dillington Car, Gressenhall SSSI. The river lies within the North Norfolk Natural Area and North West Norfolk and Fenland Character Area that recognise the landscape and geological controls on the environment. The Biodiversity Action Plan (BAP) habitats present in the area include chalk rivers, reedbeds and floodplain/grazing marsh. The statutory and non-statutory drivers for river conservation and restoration of the River Wensum are summarised in Table 4.3.

Recently, English Nature and the Environment Agency, have worked together to develop a national strategy for the restoration of physical and geomorphological favourable conditions on river SSSIs (Mainstone pers comm. 2005). **It is vital to understand this Geomorphological Appraisal within the context of the strategy**. Under the proposed strategy a series of stages are followed leading to an agreed 'Action Plan'. Specifically on each river SSSI, the strategy will:

- undertake a geomorphological assessment, using fluvial audit where necessary, to identify problem areas;
- establish common standards monitoring sites (where RHS data will be used) on problem areas identified by fluvial audit;

- set favourable condition targets for physical habitat;
- map flood risk constraints to physical restoration;
- determine the physical measures required to attain favourable condition across the whole site;
- identify mechanisms and funding streams available/required to deliver these measures and map these spatially;
- seek agreement with landowners and other stakeholders over willingness to accept physical changes if implementing mechanism can be secured;
- draw up an agreed action plan following consultation with landowners/stakeholders, secure the necessary implementing mechanisms, and schedule the works;
- judge the action plan and schedule in the context of an assessment of "unfavourable recovering";
- deliver the action required;
- monitor to assess changes in condition and the effectiveness of the measures adopted.

Fluvial audit and geomorphological dynamics assessment are not designed to determine detailed restoration plans but are the recognised method for determining the optimum channel from necessary to support the physical habitats of a SSSI.

Table 4.3: Statutory and non-statutory conservation drivers of conservation and restoration for the River Wensum.

Statutory/non statutory drivers	Conservation target
SAC Designation	The Conservation Objectives for the European interest features on the SSSI are: to maintain*, in favourable condition, the: • Water courses of plain to montane levels with the *Ranunculion fluitantis* and *Callitricho-Batrachion* vegetation to maintain*, in favourable condition, the habitats for the population of: • Bullhead (*Cottus gobio*) • Brook lamprey (*Lampetra planeri*) • White-clawed crayfish (*Austropotamobius pallipes*) • Desmoulin's whorl snail (*Vertigo moulinsiana*) *maintenance implies restoration, if the feature is not in favourable condition. PDFs of English Nature publications on the ecology and monitoring of the five European features can be found on the English Nature internet site at: www.english-nature.org.uk These can be located by navigating through special sites, Life Projects, Life in UK Rivers, publications.

Statutory/non statutory drivers	Conservation target
SSSI Designation	• Flow: Flow regime should be characteristic of the river. Levels of abstraction should not exceed the generic thresholds laid down for moderately sensitive SSSI rivers by national guidance. • Water quality: Biological GQA Class b; Chemical GQA Class B; No unnaturally high loads of suspended solids • Phosphate: An annual average phosphate concentration of 0.05mg/l from the upstream limits of the SSSI to the confluence of the River Wensum with the White Water (the tributary that drains from East Dereham), and 0.1mg/l from that confluence to the downstream limit of the SSSI. • Siltation: No excessive siltation. Channels should contain characteristic levels of fine sediment for the river type • Channel from: Channel form should be generally characteristic of river type, with predominantly unmodified plan-form and profile. Bank and riparian zone vegetation structure should be near-natural.
UK Biodiversity Action Plan	The objectives of the UK National Chalk Rivers Habitat Action Plan are: • Maintain the characteristic plants and animals of chalk rivers, including their winterbourne stretches. • Restore all rivers notified as SSSI to favourable condition. • Restore important non-SSSI rivers to favourable condition. There are a large number of national/Norfolk Habitat and Species Action Plans relevant to the Wensum, including those for chalk rivers, floodplain and coastal grazing marsh, reed-bed, fen, otter, water vole, Desmoulin's whorl snail, white-clawed crayfish. All these SAP/HAPs have targets and objectives (www.norfolkbiodiversity.org)
North Norfolk Natural Area Profile	• Identify and promote flows necessary to sustain geomorphological and ecological interest of the system. • Identify, maintain, enhance, and restore both natural and man-made riverine features which provide ecological and conservation interest. • Ensure protection, enhancement and restoration of habitat features during the design and implementation of flood defence schemes. • Restore arable land adjacent to rivers back to pasture to reduce silt loading and improve habitats. • Manage associated dyke systems on a regular but not intensive regime.
Environment Agency	• To sustain and where appropriate enhance or restore the habitat diversity within the water environment. • To provide an environmental assessment and recommendations to ensure the maintenance and enhancement of conservation interest to flood defence. • Develop Water Level Management Plans to protect the ecology of sensitive wetlands. • Fisheries Action Plan for the Wensum.
European Water Framework Directive	• Take appropriate measures to ensure water bodies attain Good Ecological Status by 2015. • Establish a Programme of Measures to ensure water bodies attain Good Ecological Status.
European Habitat Directive	• Monitor, assess and enhance Favourable Condition of SSSI/SAC rivers. • Review of consents under Regulation 50 of the Habitats Regulations is another major driver for the Environment Agency and other competent authorities.
UK Gov Public Service Agreement (PSA) Targets	• 95% SSSI in Favourable Condition by 2010.

Statutory/non statutory drivers	Conservation target
Planning Policy Statement 9: Biodiversity and Geological Conservation	• PPS9 sets out the Government's national policies on protection of biodiversity and geological conservation through the planning system. • Plan policies on the form and location of development should take a strategic approach to the conservation, enhancement and restoration of biodiversity and geology.
Environmental Stewardship Targeting - Mid Norfolk	High Level Scheme applications for environmentally sensitive farming practice: • maintain or enhance Sites of Special Scientific Interest (SSSIs). • Improvement of water quality through reduction of soil erosion (priority: R. Wensum catchment) and leaching of nutrients. • Conservation of landscape and wildlife associated with arable farming; in particular maintaining locally distinctive landscapes and reversing the decline in farmland birds. • Protection of historic and archaeological sites. • Access – provide further recreational facilities, to promote greater appreciation of the countryside. • Maintenance and restoration of BAP priority habitats. Conservation of BAP priority and locally important species. (Defra 2005).

4.4 River channel maintenance

River maintenance is the process of maintaining, through a set of actions, the land drainage, flood protection or integrity of structures along a watercourse. It is usually undertaken as a rolling programme interspersed with necessary "breakdown" maintenance often initiated by flood events. On the River Wensum, the maintenance regime is effectively split into:

- 'Main River', which is largely maintained by the Environment Agency.
- 'Main Drains' (132km), which are maintained by the River Wensum IDB.
- Network of secondary farm ditches that drain into the IDB drainage network and which are maintained by landowners.

Maintenance on the Wensum typically includes weed-cutting in June - November with the extent of weed-cutting determined by the conservation value and benefits to flood protection. (The Environment Agency is responsible for flood risk management for people and property, not land drainage. However, it is recognised that flood protection work can in some circumstances have positive benefits for land drainage). For example, in mill impounded reaches the maximum that the Environment Agency cuts is normally two thirds of the wetted channel width. In steeper gradient reaches with faster velocities, up to a 50% weed cut in the centre of the channel is undertaken. For both impounded and free-flowing reaches there are some exceptions (eg critical urban reaches, or where there are severe 'pinch-points') where a greater proportion of the vegetation is cut. Weed-cutting proceeds upstream from Norwich to Attlebridge (commencing June) followed by Lenwade to Southmill Farm upstream of Fakenham. In recent years a second weed-cut is undertaken in the lower reaches towards the end of the summer. The weed-cut is made using a boat, which is able to cut a central channel, leaving the margins as undisturbed wildlife habitat. Additional maintenance is undertaken to desilt areas where channel capacity is thought to be unacceptably reduced; remove woody debris (primarily fallen trees) from the channel; and for the maintenance of bankside trees. With regard to the IDB drains, a rolling programme of desilting and weed removal is undertaken, in line with the King's Lynn Consortium of Internal Drainage Board's booklet; Standard Maintenance Operations.

The benefits of weed cutting and de-silting are primarily to reduce the flood risk to people and property. It may also aid land drainage during summer when gravity drainage is required in the IDB drain network (Bloomfield pers comm., Carrick pers comm.). High summer water levels pond back up the lower courses of IDB drains from higher water levels in Main River. This prevents gravity drainage of meadows via IDB drains and farm secondary drains and may result in deteriorating grazing. Carrick (pers comm.) estimates that IDB drains require 1ft (0.34m) freeboard in them to get gravity drainage in summer.

The case for the flood risk management benefits of river maintenance are based on the assumption that the worse case flood risk occurs under high weed growth and thunderstorms during the summer, and that the current level of flood protection is "dependant on maintaining the current channel dimensions". However, the recent hydraulic model study (Environment Agency 2003) for the Wensum concludes that large magnitude flood flows (>1:50yr) are relatively insensitive to increases in roughness within the model and hence weed growth is not a major contributor to flood levels at the higher return periods. This is supported too by the low gradient flood level growth curves that predict relatively little increase in flood level for a given increase in discharge – levels primarily being controlled by topography rather than channel roughness at high flood flows. Similarly, modelling of flood levels after 600mm de-silting demonstrated only limited reduction in the 1:100yr flood levels in Norwich that were within the model uncertainty (Bloomfield pers comm.). This conclusion is limited to the Norwich area only, as covered by the Norwich modelling, and not to the whole of the Wensum. The above comment is therefore not in context. Furthermore, the modelling study highlights the benefit of retaining a hydraulically rougher channel in the catchments of the Wensum upstream of the Blackwater confluence, and in the Wendling Beck, since this influences the flood attenuation time, leading to reduction in downstream flood peak, though again the values are within the likely model uncertainty. The current level of flood protection is relatively high for much of the land use adjacent to the Wensum. For example, a 1:19yr flood event in Feb 2004 was contained within the channel along much of the Wensum (Bloomfield pers comm.). However, Dryden (pers comm.) suggests that this condition related primarily to the urban developed area during the event and that the undeveloped floodplain was (mostly) fully utilised. The existing model of the Wensum represents an important tool for testing a range of maintenance and restoration options under current and future hydrological regimes.

5 Geomorphological processes

The geomorphology of the River Wensum is composed of the processes of sediment production (sources), transport and storage (deposition) and the resulting physical form of the river channel and floodplain. Central to understanding these is to quantify the dynamics of sediment transport through the river system and to establish the sources and sinks (storage) of sediment within the channel network. Once these have been identified it becomes possible to interpret the channel morphology.

5.1 Sediment transport in the river network

A fundamental question for any morphological restoration is whether the channel boundaries are stable relative to the flow regime. If the boundary is stable under all flows, then the channel will be unable to make an unassisted recovery to a more natural form. Instead the channel boundary will remain stable under a given flow regime with a mobile fraction composed of finer sands and silts. Alternatively if the channel boundary is mobile under high flows, then provided that a supply of coarse sediment is available, the river will be capable of recreating more natural channel morphology.

The evidence required to assess this would ideally include actual measurement of sediment fluxes over the flow regime. In the absence of this data it is possible to estimate the depths of flow required to mobilise the bed material and compare these to those observed under bankfull floods. A common approach is to utilise a tractive force method based on mobilising the median diameter of the surface material on the river bed (Komar, 1987; Petit, 1990). The method adopted by this study utilised surveyed cross-sections along the Wensum, together with measurements of bed material grainsize. ISIS hydrological modelling outputs for bankfull, Q5, Q50 and Q100 recurrence interval were used as input.

The maximum particle mobilised can be estimated by rearranging the Shields equation:

$$d_{max} = \tau / \theta \; (\rho_s - \rho) g D_{50} \qquad (1)$$

d_{max} is the maximum particle size mobilised by bankfull floods (mm), g is the gravitational acceleration in ms^{-2}, τ is the bankfull shear stress (Nm^{-2}) and is calculated from

$$\tau = \rho \, gRS \qquad (2)$$

θ is the Shields entrainment function which ranges in value from 0.03 for loose gravels to 0.06 for packed gravel. ρ_s and ρ are the densities of sediment and water and are taken as 1650 and 1000 kgm^{-3} respectively.

The shear stress calculated in equation (2) is widely recognised to over-estimate that which is available for entrainment of bed material (Richards, 1982; Petit, 1990) since it does not account for energy losses resulting from vegetation, form roughness and internal friction between moving water bodies. Petit (1990) following Richards (1982); provides a correction factor based on the ratio between grainscale roughness and the remaining roughness contribution;

$$\tau' = \tau . K^{3/2} \qquad (3)$$

Where K is a correction factor (n'/n_o) where n_o is the total Mannings roughness and n' is the grain roughness calculated from:

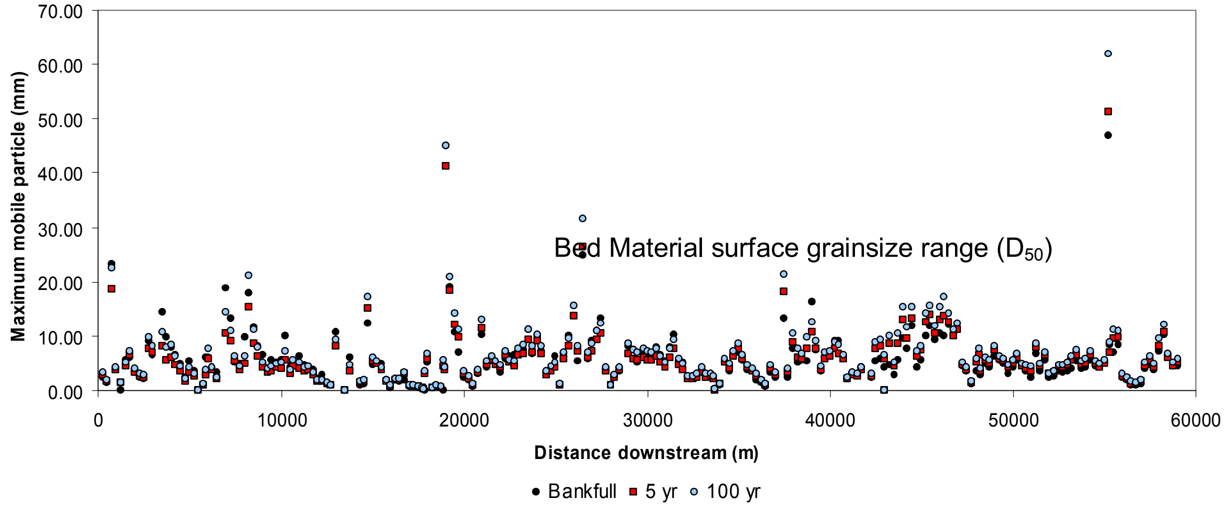
$$n' = 0.051 D_{50}^{1/6} \qquad (4)$$

In the absence of spatially variable data on grainsize and the hydraulic variables to calculate *n,* a value for *K* of 0.5 was used based on the neighbouring River Nar.

On the basis of this analysis it can be demonstrated that in the majority of sites surveyed the coarse fraction of the bed material will be stable under flood conditions (Figure 5.1). Exceptions appear at sites immediately downstream of mills where gradients are locally steeper. (Figure 5.1b). The mill ponded reaches are associated with drops in shear stress, and hence sediment transport potential and maximum mobile grainsize. The silted reach through Great Ryburgh to Bintree Mill is explained by the backwatering effect from Ryburgh and Bintree mills.

The bed stability of lowland groundwater dominated rivers has been reported by German & Sear (2003) for the River Wylye, a chalk stream with greensand headwaters. Similarly, Acornley & Sear (1999) reported low rates of bedload transport in the groundwater dominated River Test which were characterised by sands and Tufa fragments. The coarse bed framework gravels remained immobile. This analysis supports the conclusion that:

the gravel bed of the River Wensum, in its current and semi-natural state, is largely stable across all flows by virtue of the low gradient and discharge.



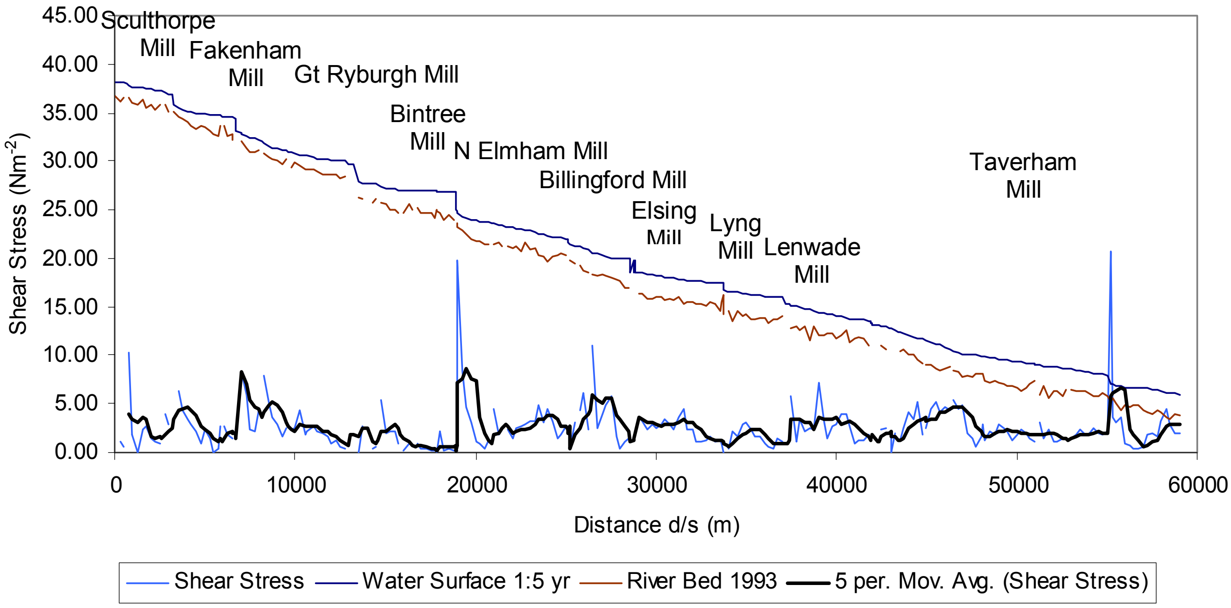


Figure 5.1 **a)** Comparison between the maximum predicted mobile particles and the median diameter of coarse surface bed material for cross-sections of the River Wensum illustrating the stability of the gravel bed under large flood events. **b)** Shear stress changes downstream, demonstrating the effect of mills on transport potential. The D_{50} is the median bed material size and is typically the maximum size fraction mobile for a bankfull discharge.