5.1.1 Fine sediment transport

As part of the geomorphological dynamics assessment, suspended sediment loads were monitored via a calibrated turbidity probe located at the gauging station at Fakenham, and from the turbidity datasets derived from Anglian Water PWS samples collected at 15 minute intervals at Costessey. To convert this data into a record of suspended solids requires simultaneous collection of suspended sediment samples. This was undertaken by Robin Goolden (Project Officer for the Wensum Valley Project). Unfortunately only three samples were collected and these only ranged between 50-81 mgl^{-1} suspended solids. Calibration was therefore not possible, but remains a future option. Historic turbidity records are available from Anglian Water, though only six years of record were provided up to the point of reporting. Longer term and more recent records exist and it is recommended that these should be analysed. Anglian Water Services did not specify how much historical data they hold but there is the possibility that records could extend back to the inception of the PWS in the 1950's.

The data from Anglian Water was processed and cleaned in order to remove the bias due to drifts in the calibration between turbidity and water discharge. These arise due to changes in the method of sampling or due to problems with the instrumentation. The cleaned dataset is presented in Figure 5.2 together with the flow record at the Costessey gauging station. Turbidity can be used as a surrogate for sediment load. In this instance the turbidity record clearly responds to increases in runoff generated by storm events in the catchment. Turbidity is generally highest at the start of the increase in discharge and generally peaks before the peak in flow. This arises due to the exhaustion of suspended loads that have accumulated in the channel over the previous autumn. The peaks in discharge relate to peaks in turbidity which demonstrates that heavy rainfall events provoke a rapid change in turbidity.

Figure 5.3 presents a double-mass plot of cumulative flow and cumulative turbidity. Breaks of slope on this figure indicate where the turbidity increases or decreases above the general relationship. Two increases occur which suggest possible increases in the transport of suspended sediment from the catchment in the period around winter 1999/2000, and again in autumn 2000-2001. A reduction in the rate of increase in turbidity back to pre 2000 levels occurs in March 2001. Unfortunately it is not possible to determine what the cause of the first increase is, but the second clearly relates to the "millennium floods". This analysis does however demonstrate the value of this type of information, and careful analysis might help determine longer term trends in the turbidity records and potentially, correlations with changes in land use and or channel management practice.

Leeks and Walling (1999) assessed the potential transfer functions for converting turbidity units into suspended solids concentrations. In the absence of a full calibration, his function is used here to provide an estimate of the suspended solids load for the period 2003/04 and for the study period (Table 5.1). The total suspended sediment loads for the Wensum at Costessey range between 1994 tonnes to over 3000 tonnes per annum with most of this load transported during high flows between October and March. These values equate to catchment yields of 3.3-5.1 $T\ km^{-2}\ yr^{-1}$ which are within the lower limit of published yields for chalk rivers (Acornley & Sear 1999).

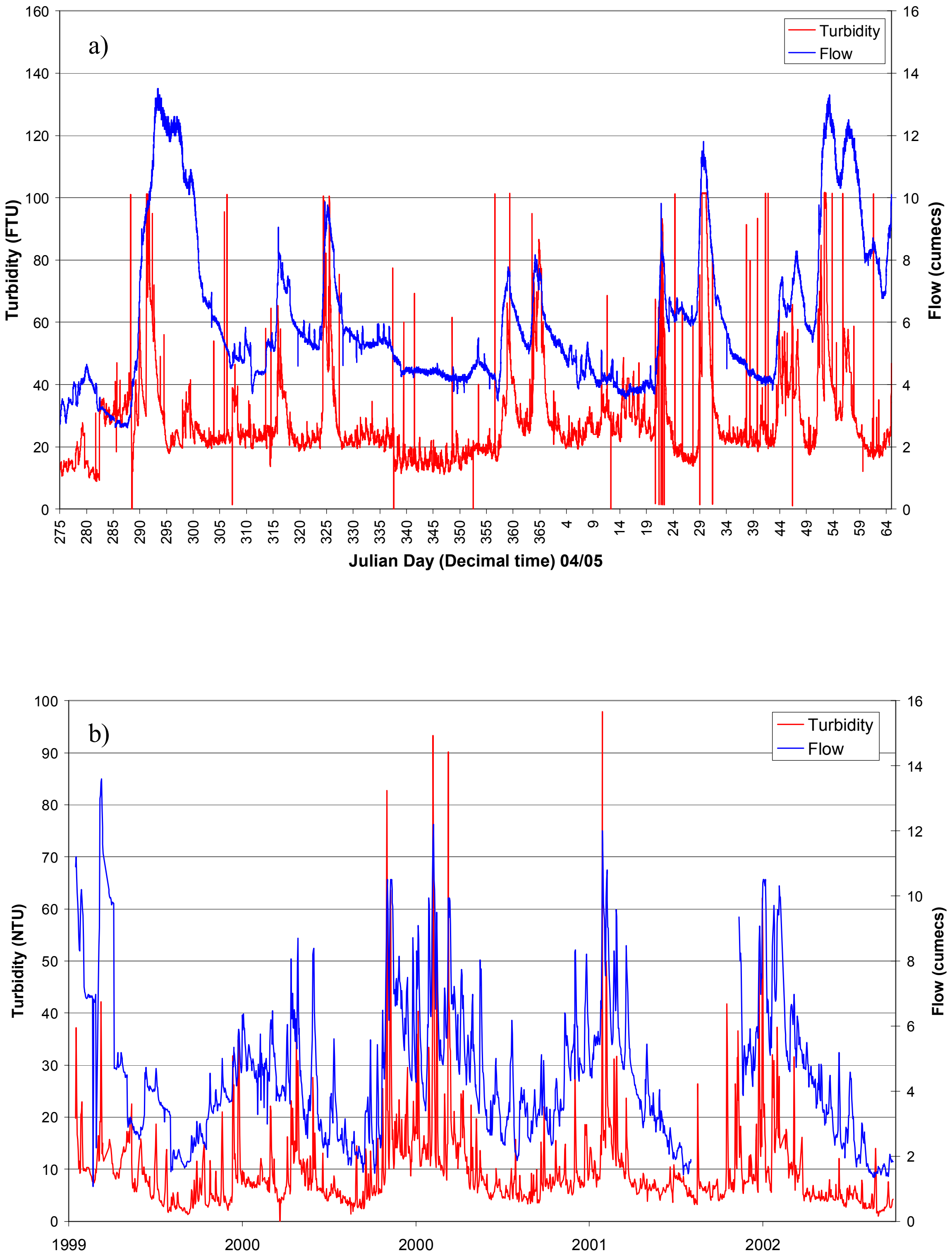

Figure 5.2 Time series of turbidity and discharge at Costessey for a) the period of the study (1/10/04 – 05/03/05) and b) for the period 1999 - October 2002. Turbidity data provided by Anglian Water. Increases in turbidity show event-based fluctuations associated with increases in discharge and seasonal fluctuations associated with release of groundwater. The autumn 2000 – 2001 "millennium" floods are associated with an extended period of high turbidity. In Figure 5.2a the Julian Day axis is the count of days from 1 January (modified to the year).

Table 5.1 Estimated suspended sediment solids loads for the period 2003/04. The 'water year' is the hydrologic period from October to September.

	Water Year 03/04	Winter (0ct-Mar) 03/04	Summer (Mar-Sept) 03/04	Period Oct 3-5 Mar 04	Period Oct 4-5 Mar 05
Total load (tonnes)	1994.2	1307.6	686.6	**1146.0**	**2972.1**
Mean flow (cumecs)	4.3	5.2	3.4	5.2	6.1
Maximum Flow	15	15	10	15	13.5
Minimum Flow	1.1	1.3	1.1	1.3	2.6
Mean turbidity (FTU)	10.6	10.8	10.4	**10.6**	**28.2**
Maximum Turbidity	100.7	99.2	100.7	99.2	101.7
Minimum Turbidity	0	0	0	0	0
Mean SSC (mg/l)	12.4	12.6	12.1	**12.4**	**33.0**
Maximum SSC	117.8	116.0	117.8	116.0	119.0
Minimum SSC	0	0	0	0	0

Source: Anglian Water

Sand transport in the catchment occurs by two processes:

1) **bed load transport** where the coarse sand remains in contact with the river bed and moves as threads or sheets over the stable gravel bed.

2) **suspended sediment transport** where the finer sand sizes are transported in the water column, suspended by turbulent eddies.

Evidence for suspension of sand comes from the presence of this material in the floodplain while bed load transport is observed in reaches in the form of dune fields (Figure 5.4).

A provisional assessment of the capacity of the River Wensum to transport sand-sized sediment was undertaken using cross-sectional areas derived from the fluvial audit estimates of channel width and depth. A more comprehensive modelling exercise using the surveyed data from the ISIS hydrological model (Environment Agency 2003) was not possible in this report, but would be a logical next step and it is recommended that this should be undertaken to provide estimates of the impacts of increased weed growth and channel restoration options on sediment transport rates. Sediment transport of sand sized material was calculated using the Ackers-White (Ackers & White, 1973) bedload transport equation with a grainsize of 1.4mm to represent the sand fraction. The data used were derived from bankfull dimensions and thus represent maximum bedload transport capacities for the River Wensum at the sites corresponding to Fakenham, Billingford, and Lenwade. These were chosen on the basis of bankfull discharge estimates derived for the ISIS hydrological model (Environment Agency 2003). The estimated bankfull sand transport capacity is presented in Table 5.2. This demonstrates that sand transport capacity increases with catchment area, which corresponds to an increase in bankfull discharge. Sites towards the headwaters, though slightly steeper do not have such a large bankfull discharge and are therefore less able to transport sands. This is an important consideration for management of the River Wensum since reductions in discharge either due to climate change or abstraction, will result in reduced fine sediment transport capacity and increased accumulation. Similarly, reduction in gradient through re-meandering in any restoration will also result in a decrease in transport capacity and in the absence of fine sediment source control the accumulation of fine sediments.

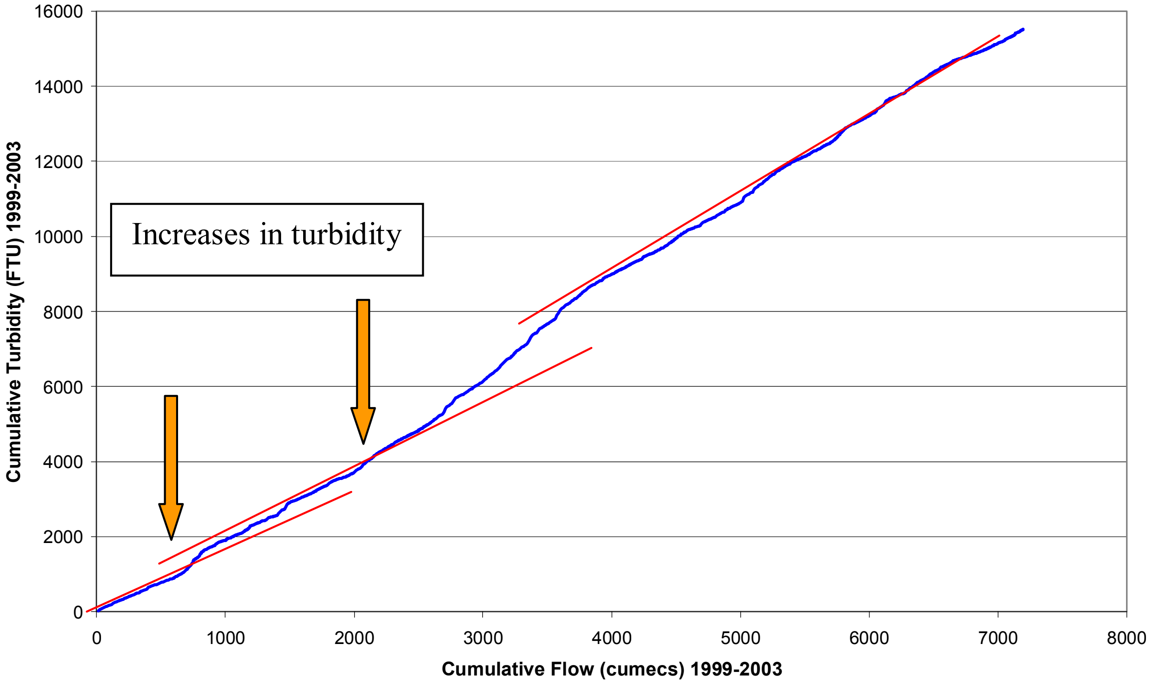

Figure 5.3 Double mass plot of flow and turbidity at Costessey, for the period 1999 – 2002 based on Anglian Water records. Two periods of increased turbidity are evident; the second major increase is associated with the 'millennium floods' of autumn 2000.

Figure 5.4 Sand transport as bed load moving in a series of dunes in the upper Wensum catchment. (Reach W1064).

Table 5.2: Estimated sand transport capacity at bankfull for three sites representative of the upper catchment and at major increases in discharge associated with tributary inputs.

Location	**Q bankfull (cumecs)**	**Sand transport rate at bankfull (kgs^{-1})**
Wensum at Fakenham	4.2	0.24
Wensum d/s of Wendling beck	10	0.65
Wensum d/s of Whitewater	18.8	1.40

5.2 Sediment sources

An important aspect of the sediment system of a river is the source of the material available for transport. This material has ultimately to enter the river network, though much is simply stored within the catchment and does not find its way into the network. The component of this material that enters the river network provides the supply of sediment that can be utilized by the river to create physical habitat. It is important to stress that not all of the material that enters a river as a source is able to be mobilised by the river, in which case it is locally deposited at the entry point.

The River Wensum has three potential sources of fine sediment – channel bed, channel banks and catchment sources. Each requires assessment in terms of contribution to the river sediment load.

5.2.1 Bank erosion sources

Bank erosion in the River Wensum was assessed in two ways:

1) Analysis of lateral channel migration over long time scales through digital overlay of the 2000 OS Land-Line channel outline over a digitised first edition OS map from 1898.

2) Through field survey of the length and type of bank erosion observed in the walk through survey.

The historical analysis revealed very limited evidence of natural channel migration.

The contemporary field survey identified erosion processes. These are dominated by weathering of the bank face where unvegetated, poaching by livestock and fluvial scour by river processes. The total length of eroding river bank on the River Wensum at the time of survey is 6.4 km or 4.0% of the total bank length. The dominant bank material for the River Wensum is fine sands and silt, with limited areas of gravel where the channel has been dredged below the former bed level. The bank materials in the neighbouring River Nar catchment are reported by Harvey (1967) as having a significant silt/clay component (23-61% by weight) which is known to increase the resistance of bank material to erosion by fluvial scour. Figure 5.5 illustrates the downstream trend in bank material composition along the Wensum. This is unlikely to change over time, except by human modification or the fluctuation in river bed revealing more or less of the lower gravel layers. On average the banks are 51% silt/clay, 30% sand and 19% gravel. Additional resistance to bank erosion is provided by the extensive communities of riparian vegetation and marginal emergent aquatic plants, which even in winter afford protection from scour. If one assumes a conservative estimate of bank retreat at 0.5 cm/year, a not unreasonable value for lowland low energy streams (Sear and others 2004), then the total potential contribution from bank sources for the Wensum can be estimated by multiplying the bank height and erosion length by the erosion rate. In this instance the volume is 192 m^3 or 509 tonnes per annum delivered from bank erosion sources, of which approximately 101 m^3 would be silts and clays, transported as suspended load; 58 m^3 would be sand, transported as suspended and bedload; and 37 m^3 would be gravel. These values are first order approximations but serve to illustrate the potential total supply from bank erosion. Field evidence suggests that little gravel is supplied, and that much of the bank erosion is produced by weathering of the bank face by freeze/thaw and desiccation processes.

Table 5.3 provides comparison with other rivers for which equivalent fluvial audits are available. The River Wensum has comparable bank erosion lengths to the rivers Wylye and Nar, and has much less bank erosion compared to other higher energy river systems.

In comparison with other river types, the Wensum has relatively little extent of bank erosion, and low rates of bank erosion. Although potentially contributing 500 tonnes per annum from this source, this is actually a small fraction of the estimated total suspended load of between 2000-3000 tonnes per annum (see above). Bank erosion is therefore a relatively unimportant source of fine sediments, and insignificant as a source of gravel on the main river. Bank erosion on steeper tributary streams, where these are subjected to modification and maintenance (eg Wendling Beck) may represent a source, but these were not surveyed within the project.

Table 5.3 Comparison of percentage of surveyed length of bank erosion for different rivers. Note the relatively low proportion of eroding banks recorded for low gradient lowland channels and chalk rivers compared to higher energy upland rivers.

River	**Relative stream energy**	**% River bank eroding**	**Source**
Wensum	Low	4.0	GeoData 2004
Wylye (Chalk)	Low	4.2	GeoData 2002
Nar (Chalk/Fen Basin)	Low	4.9	GeoData 2004
Britt (Greensand/Chalk)	Mod	6.0	GeoData 2003
Highland Water (New Forest)	Mod	9.4	GeoData 2003
Till	Mod	10.0	Newson and Orr, 2003
Caldew	High	14.8	GeoData 2001
River Ure	High	16.1	GeoData 2000
River Lune	High	18.0	Orr, 2000
Dee	High	18.2	GeoData 2004
Wharfe	High	18.7	GeoData 2001
Swale	High	25.2	GeoData 2002

5.2.2 Catchment sediment sources

In the absence of bank erosion as a major source of sediment, the other main sources are the river bed and the catchment land surface. The land surface is the ultimate origin of all sediment found in river valleys. What is important for contemporary river management is, the extent to which sediment sources are still active on the catchment surface; and secondly the extent to which these are connected to the river network. In the River Wensum, the catchment surface is covered with former glacial deposits, providing a range of mostly fine sediments in the form of soils of varying textures and grainsize composition (see Section 3.1). Some gravel also outcrops on the surface. Potentially therefore, the catchment surface under current land use and land management is a source of both fine and coarse sediments. However, the subdued topography results in limited erosion and transport of the coarser materials. The main sediments in movement over the catchment surface are in the coarse sand – clay size range, with minor quantities of fine-medium gravels washed out of fields and road verges, but generally failing to connect with the river network.

While potential sediment sources in a given a catchment can be readily identified, these do not become actual sources unless they are connected to the river network. As part of the fluvial audit, a field reconnaissance of fine sediment ingress points and the dominant sediment-type at these points was mapped along the entire river. In addition, fine sediment sampling of active sources of sediment were monitored over a storm event in January 2005 as part of a monitoring programme established over the study period. In the event the dry autumn/winter prevented assessment of many catchment sediment sources.

Examples of a sediment input and source recorded during a heavy rainfall event on 28 January 2005 in the Wensum catchment are presented in Table 5.4 below and in Figure 5.6. These illustrate sources derived from runoff erosion of arable fields and erosion of roadside verges by traffic.

The values for sediment production over a 30 minute rain event are indicative and are not considered to be accurate. Nevertheless, the values demonstrate the potential for delivery of significant quantities of fine sediment from single fields during a single short rain event. Assuming that these transport rates are indicative of the supply to the River Wensum it can be seen that values of 0.05 – 0.31 kg/s are generally less than the calculated bankfull transport rate for the river (0.24-1.4 kg/s). This suggests that on entry to the Wensum, catchment derived fine sediments are mobile, and can thus be transported downstream of an ingress point until either the flows subside and the fines are deposited on the bed, or the local transport rates decrease and the sediments are deposited. This model of transport helps explain the accumulation of fines upstream of mill structures, and the relatively “clean” areas of channel unaffected by ponding from the mills. It also supports the notion that in a natural state, the channel is capable of flushing fine sediments during high flow periods.

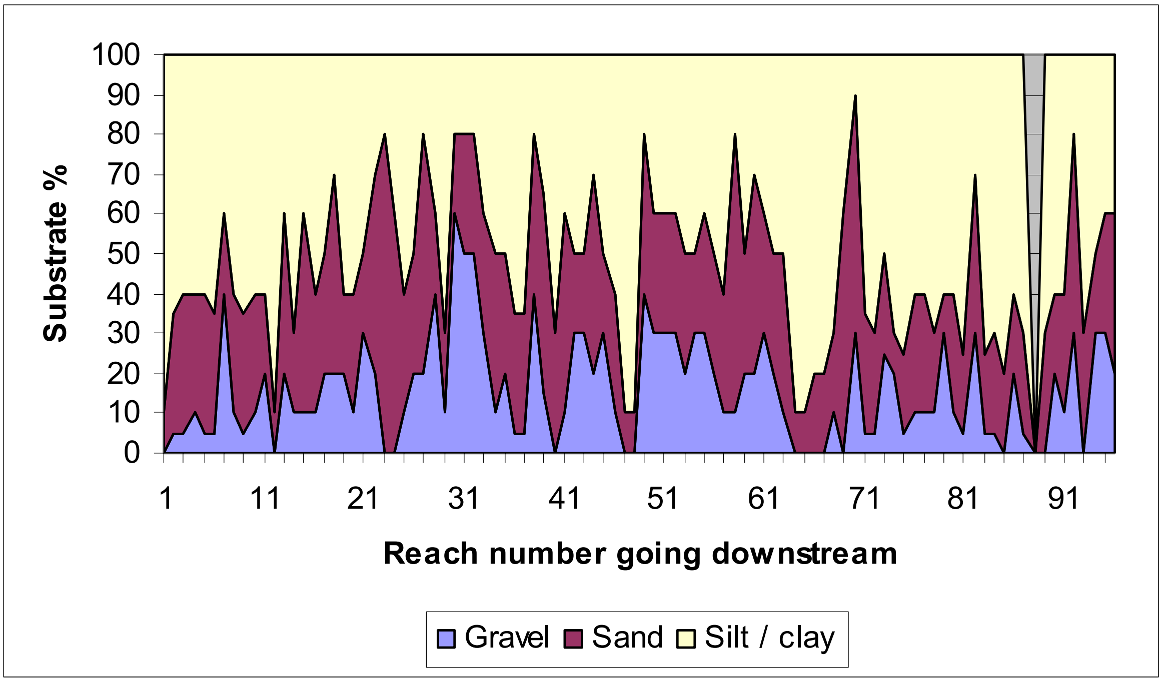

Figure 5.5 Variations in bank material composition along the Wensum, recorded in the 1990 River Corridor (1990) survey.

Figure 5.6 Fine sediment runoff from arable fields and road side verges. Note routeway into road side drain. Photo a) Gateley, TF972248. Photo b) Guist Bottom, TF987267.

Table 5.4: Examples of fine sediment runoff from land use types in the River Wensum and the neighbouring River Nar catchment (winter 2004/2005). Values of sediment delivery are based on measured discharges for each flow. Note that these values are subject to uncertainty and error in estimation. Relative values are believed to be robust.

River	Location	Date	Source	Sediment Concentration (mgl^{-1})	Load (kg) delivered in 30 minutes (figures in brackets are rates in kg/s)
Wensum	TF964273 Great Ryburgh	28/01/05	Arable Field Runoff	2540	91.4 (0.051)
Wensum	TF965265 Great Ryburgh	28/01/05	Arable Field Runoff	200	21.6 (0.012)
Wensum	TF972248 Gateley	28/01/05	Arable Field Runoff	2277	553.3 (0.312)
Wensum	TF987267 Guist Bottom	28/01/05	Arable Field Runoff	689	310.1(0.172)
Nar	West Acre Bridge	28/09/04	Pig Unit + Road Runoff into River Nar.	9740	3103.2 (1.72)
Nar	West Acre Bridge	28/09/04	Channel upstream of input point.	28	28.4 (0.016)

Critical conditions for catchment sediment delivery are:

1) Delivery of fine sediment at high transport rates into river reaches with low sediment transport capacity (mill ponded reaches).
2) Delivery of fine sediments at high transport rates during short intense storms that do not cause significant increases in river flow (eg summer convective storms), resulting in input exceeding transport capacity.

Examples of catchment fine sediment sources identified in the Wensum catchment by field survey include:

- Erosion of road side verges and deposits on the road network.
- Pig farm units.
- Runoff from arable and pasture fields including maize.
- Erosion of unmetalled tracks and footpaths where these discharge onto road network.
- Erosion of recently cleared drainage channels.
- Bank erosion/poaching of banks.

Current debate within UK river management agencies refers to silt pollution as a diffuse pollution issue – that is multiple unspecified sources distributed around the catchment. In lowland streams such as the Wensum, the relative lack of extensive headwater tributary networks and the presence of floodplains result in a naturally low connectivity between the river and the adjacent slopes. Fine sediment ingress is therefore better described as a set of point sources of sediment discharge (German & Sear 2003).These points of ingress occur where runoff from the catchment surface intersects with the river and existing drainage network. Ingress points located during this survey include:

- Tributary confluences (few in chalk streams and rivers but significant).
- Road crossings where road drains discharge into the river.
- Footpaths/tracks crossing the river network.

- Points where the channel is intersected by dry valley network without the presence of a floodplain (eg Ringland).
- IDB drainage channel confluence with the Wensum main channel.
- Hillslope discharges into the main river network in the absence of a floodplain.
- Poor land management around springs that connect to the main river.

Silt ingress occurs in response to intense rainfall events on bare fields and where there is a routeway into the channel. The presence of a wide and shallow floodplain with low-intensity land use along most of the Wensum buffers the river network from fine sediment delivery from the valley sides. Exceptions exist around the tributary headwater streams where intensive arable cropping up to the river bank and field drainage network present opportunities for runoff into the river network. Routeways appear to be via the road and farm drainage network and associated network of roadside drains, with entry points possible where roads and trackways intersect with the river network. The road drainage infrastructure is maintained by Norfolk County Council; the 'Main Drains' are maintained by the Wensum Internal Drainage Board; and the management of minor field drainage systems being the responsibility of the local land owner. An important key to sediment management in the Wensum is therefore the development of an integrated approach to the management of these routeways alongside cost-effective management of the land surface in key hotspots of sediment production. Joint management of the source and the routeway into the River Wensum would provide an effective control on fine sediment ingress.

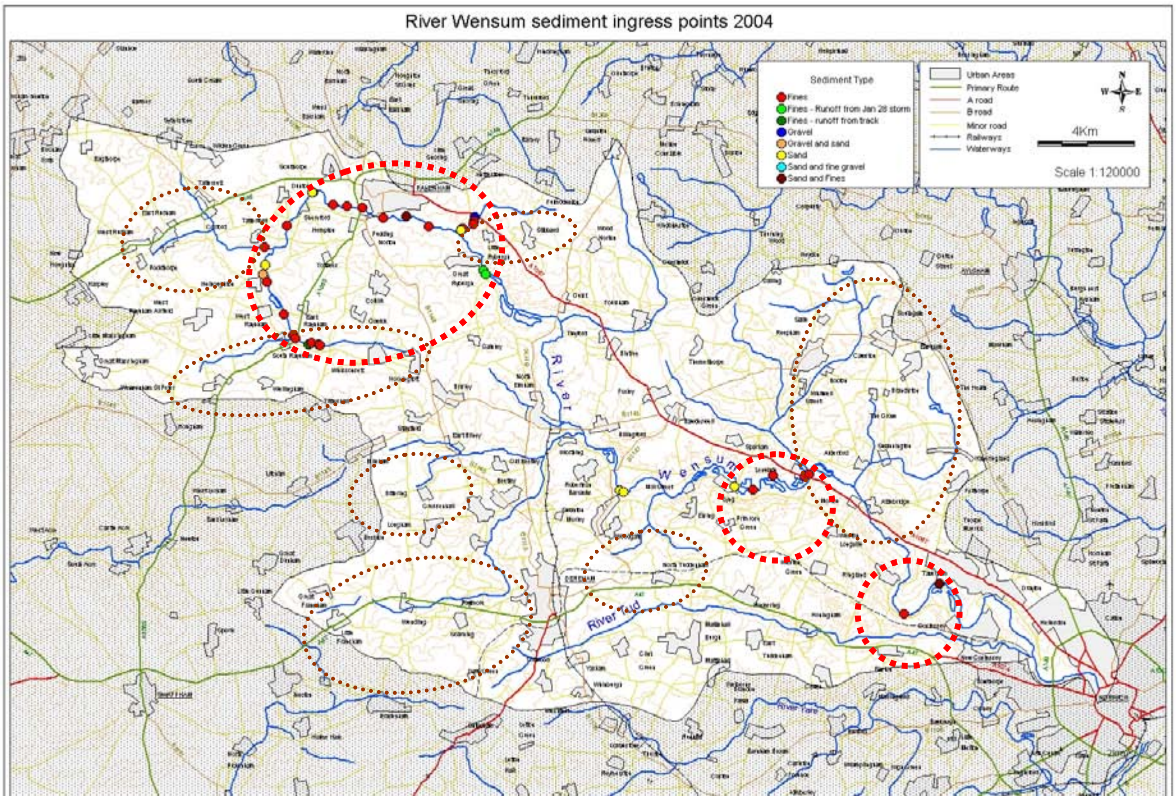

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Figure 5.7 Fine sediment ingress points identified during the 2004 fluvial audit and from discussions with Environment Agency, English Nature and chairman of the Wensum Internal Drainage Board. Red dashed lines denote concentrations of ingress points. Brown dashed areas denote potential source areas from field runoff based on soil erodibility and observed erosion reported by Boar and others 1994).

The location of sediment ingress points is given in Table 5.5.

Table 5.5: Sediment ingress points located during the fluvial audit.

Type	Easting	Northing	Location
Silt	588143.7	328883.6	Dunton
Silt	589241	330280.2	Sculthorpe
Sand	589237.6	330277.9	Sculthorpe
Fines	592245.6	329190.8	Flagmoor
Sand and Silt	593220.9	329251.9	Fakenham Common
Fines	594174.2	328851.6	Starmoor Plantation
Sand	602286.3	317635.1	Swanton Morley
Sand	602448.61	317581.27	Swanton Morley
Fines	607940.7	317687.5	Sparham
Fines	608813	318265.8	Walsis' Hill
Sand	607171.61	317799.16	Lyng
Fines	610151.52	318234.39	Lenwade Mill
Silt	610322.8	318326.9	Lenwade Bridge
Fines	614371.6	312421	Ringland
Sand and Fines	615874.15	313682.65	Taverham Mill
Fines	591356	329624.85	Night Common
Fines	590692.11	329679.61	Sculthorpe Fen
Fines	590111.92	329751.96	Hempton Moor
Gravel and sand	587120.85	326796.08	Helhoughton
Sand	587229.22	327213.13	Helhoughton
Gravel	596138.38	329230.12	Langor Bridge
Fines	596055.9	328920.5	Langor Bridge
Fines	595643.16	328745.05	The Carr
Sand	595538.62	328686.48	The Washpits
Fines	587206.1	327962.5	Tatterford Common
Fines	587304.85	326490.56	Helhoughton
Fines	588022.79	325092.44	West Raynham
Fines	588414.89	324221.69	South Raynham Bridge
Fines	588505.41	324078.38	South Raynham Bridge
Fines	589044.44	323841.02	Norman's Barrow
Fines	589205.89	323899.78	Norman's Barrow
Fines	589491.1	323818.1	Norman's Barrow
Fines	589562.27	323786.28	Norman’s Barrow
Fines - Jan 28 storm	596500.72	326964.57	Great Ryburgh
Fines - Jan 28 storm	596604.99	326809.17	Great Ryburgh
Fines	596098.7	329056.76	Langor Bridge

Those sediment ingress points recorded in this survey are indicated in the map at Figure 5.7, while the estimate of the type of sediment delivery ingress points is presented in Table 5.5.

Three points emerge from this study:

1. There are relatively few major point sources of fine sediment into the river network.
2. These appear to be concentrated in three zones.
3. The majority of sources are fine silts and sand with no local gravel source.

The sediment sources in the Wensum are derived from the catchment and are linked to field drainage systems, tributary inputs and road drainage.

Comparisons between Figure 5.7 and the soil map in Figure 3.3 highlights the spatial correlation between the River Wensum zones of sediment ingress with the presence of erodible sandy soils in the catchment. Evidence from storm runoff monitoring confirms that the loads produced from field and road runoff are substantial.

A key recommendation of this report is for all agencies to work with the Wensum Catchment Officer to investigate ways in which these sediment sources and ingress points can be better managed to reduce fine sediment delivery into the River Wensum.

5.2.3 The river bed as a sediment source

The river bed is a potential source of sediment to downstream reaches and requires consideration for two reasons: firstly as a source of gravels and fine sediment to downstream reaches; and secondly as a measure of fine sedimentation of the gravel bed. The degree to which river bed gravels are infiltrated by silt is an important indicator of habitat quality for many instream biota and which has been highlighted as a factor limiting fish recruitment (Econ 1999). The analysis in section 5.1 has demonstrated that the river bed of the Wensum is not an active mobile gravel bed and is therefore not a major source of gravel to downstream reaches. The implication therefore is that the bed is stable over most flows and each reach is disconnected from any upstream supply of gravel. The same analysis has also demonstrated that the coarse sand to clays are both supplied from the catchment surface and are readily transported through the river until the channel gradient drops upstream of mill weirs. Reaches may therefore be said to be connected with upstream sediment supply but disconnected by the presence of mill structures.

Two aspects of sediment supply from the river bed are now reviewed; first the availability of sediment in terms of the proportions of clay-silt-sand and gravel on the river bed, and second a measure of the fine sediment load on the surface and within the gravels at riffle/run locations, the latter being important recruitment areas for fish species such as trout, roach and grayling (Econ 1999).

Information on the proportions of different bed substrate types are available from:

1) The 1990 River Corridor Survey (Source to Norwich at 0.5 km reach interval).
2) The 2002 Macrophtye survey (500m reaches at sampling points used in report).
3) The 2004 fluvial audit survey (Source to end of SAC designation – variable reach lengths).

The approach that was adopted in all three surveys was to visually assess the proportion of the river bed that was covered by the main grainsize classes silt & clay, sand, gravel and cobble. The different sediment proportions are presented in the following sequence of figures 5.8 – 5.10. The black arrows denote the presence of mill structures, while the dotted ovals denote local “hotspots” of fine sediment accumulation on the river bed.

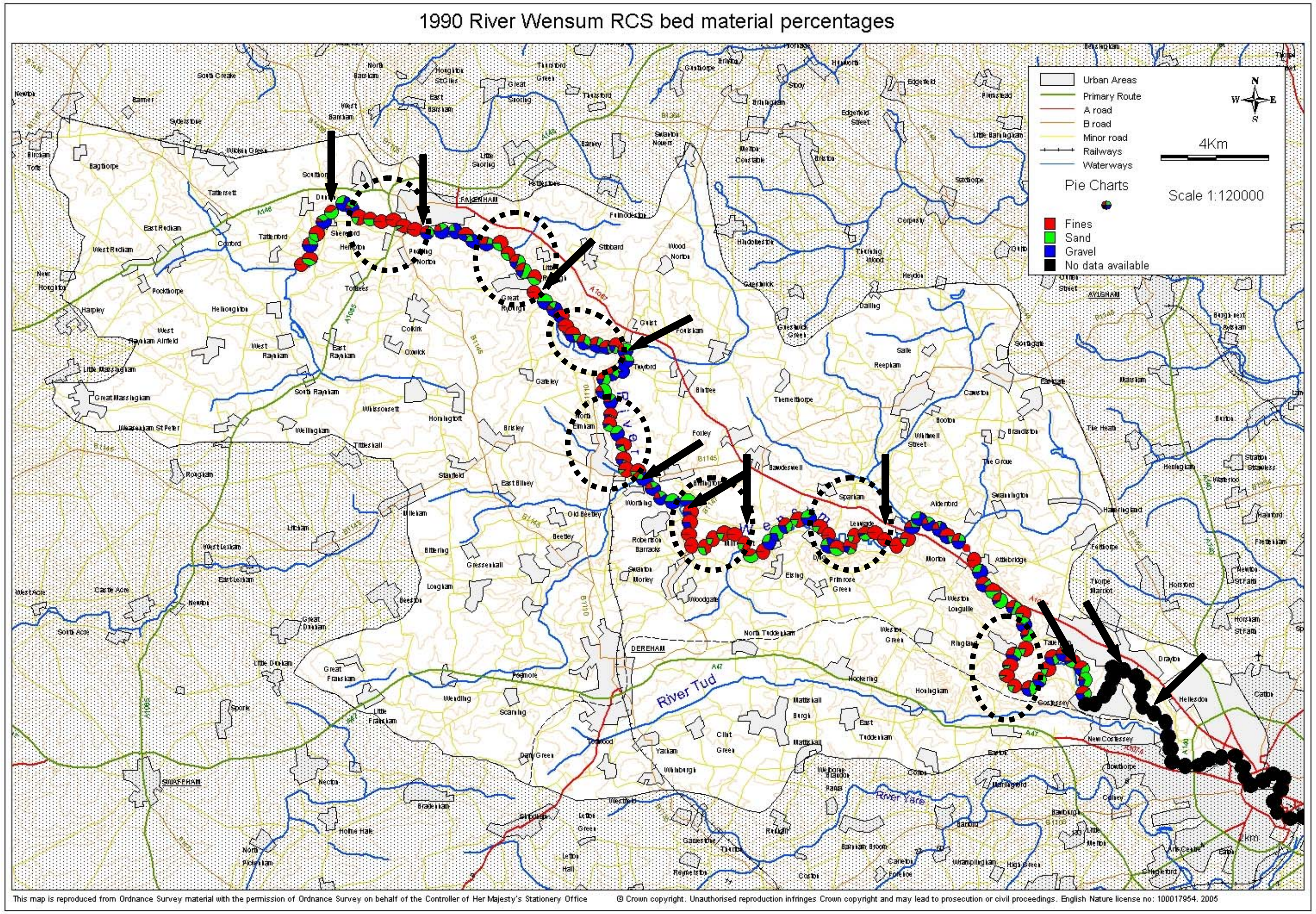
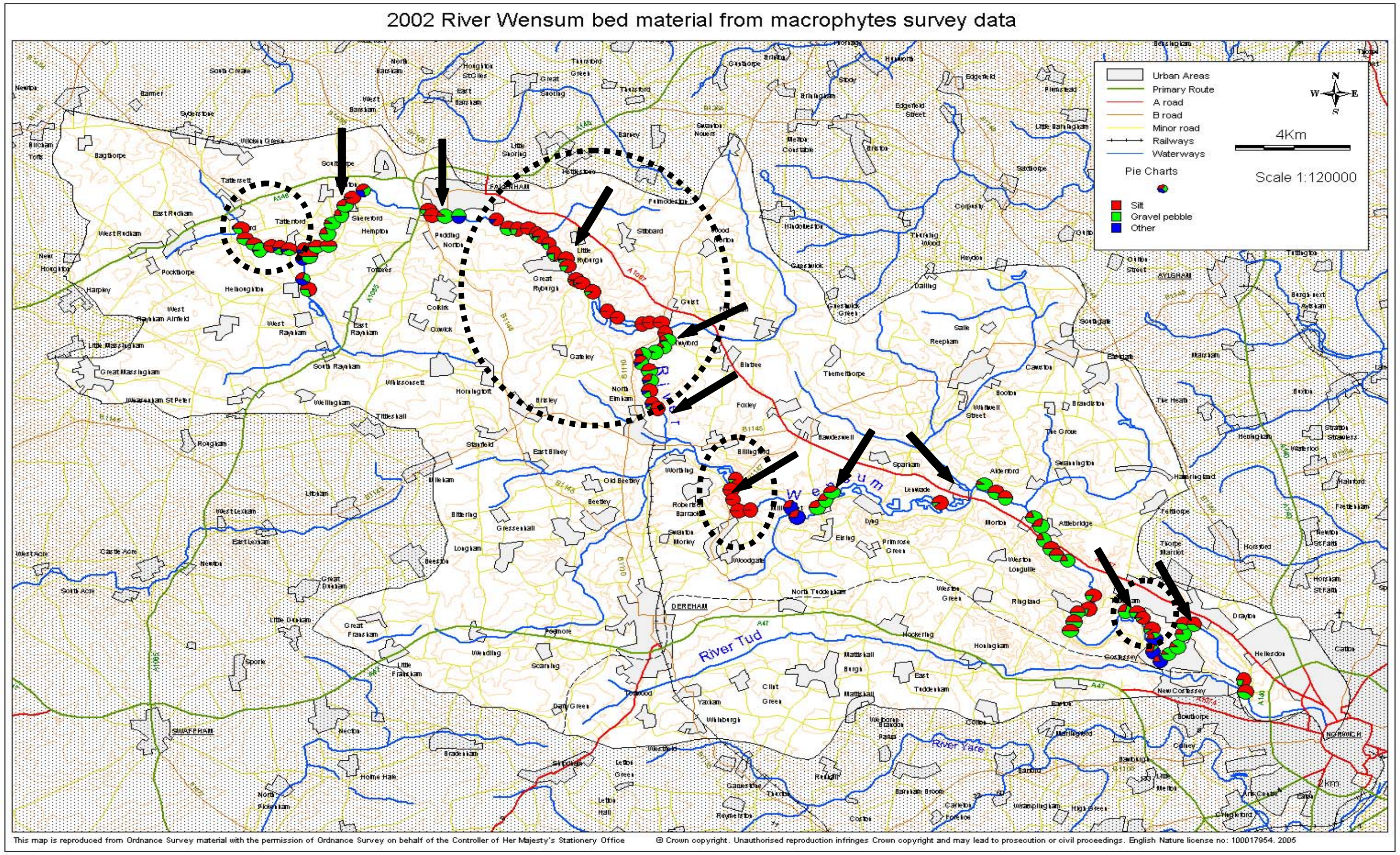


Figure 5.8 Bed substrate proportions visible in 1990. Data from the River Corridor Survey. Dotted circles highlight sand/silt dominated reaches. Black arrows locate mill structures.



2002 River Wensum bed material from macrophytes survey data

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Figure 5.9 Bed substrate proportions visible in 2002. Data from Grieve and others 2002. Macrophyte survey. Dotted circles highlight sand/silt dominated reaches. Black arrows locate mill structures.

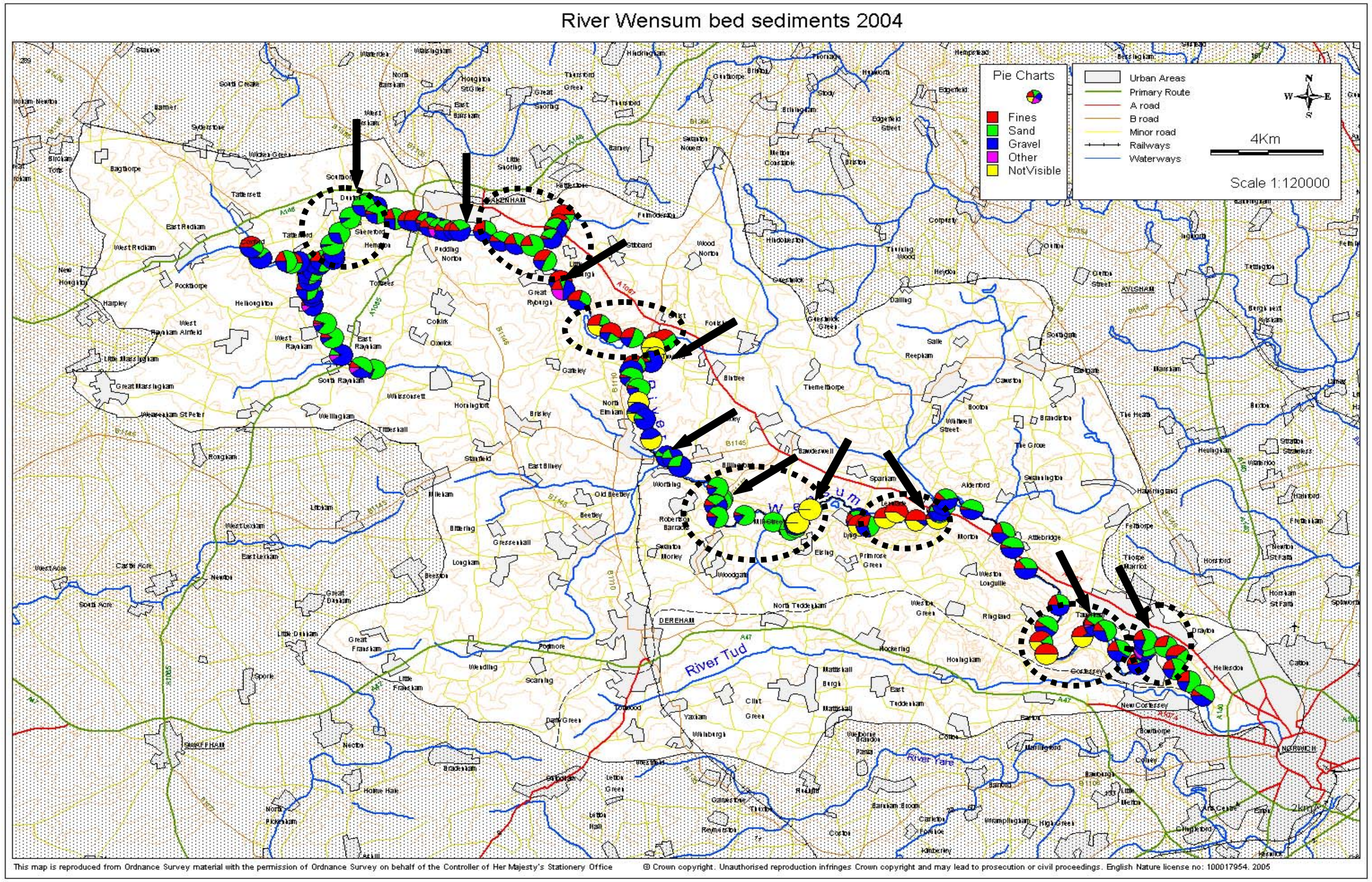

Figure 5.10 Bed substrate proportions visible in 2004. Data from fluvial audit. Note reach lengths are determined by changes in geomorphology. Dotted circles highlight sand/silt dominated reaches. Black arrows locate mill structures.

It should be recognised that because the estimates are visually determined, there is a degree of uncertainty associated with direct comparison of the values. However the broad trends downstream are believed to be robust.

It is clear from the 1990 and 2004 surveys that the large scale accumulation of fine sediments is strongly controlled by the presence of mill structures, and the associated upstream backwaters. The 2002 macrophyte survey is different in part because of the sampling framework deployed, but there is still evidence of mill related fine sediment accumulations. There is also evidence that fine sediment load on the bed of the Wensum in the area around Great Ryburgh was much more extensive in 2002 when compared to 1990 and 2004, perhaps reflecting inputs from the catchment during the autumn 2000/2001 rain events. The reach through Great Ryburgh to Bintree is strongly influenced by the mill structures that create an extensive area of low shear stress (Figure 5.1b).

Fine sediment is present throughout the system, with accumulations on the bed in the upper catchment around Helhoughton, and to a lesser extent in the River Tat. Interestingly, the Langor Drain has relatively high silt/sand loads and enters into the Wensum river reach that is shown to be dominated by fines within both the 2002 survey, and the 2004 survey. Field survey suggests the Langor Drain is a source of fine sediments to the River Wensum. Also of interest is the lack of an immediate increase in fine sediment on the stream bed downstream of the confluence with the Blackwater River, despite observed fine sediment sources within this catchment. One interpretation is that the increase in discharge is able to flush fines downstream, to accumulate at the mill structures at Elsing, Lyng and Lenwade – the section of river that is most heavily cloaked in fines in the 2004 and 1990 surveys. It is difficult though to distinguish between the influence of mill structures and the increase in fine sediment supply. The spatial distribution certainly supports the view that mill structures are the dominant control on fine sediment distribution.

The proportion of fine sediment present on the stream bed is known to vary over time. For example at Tatterford Common silt coverage of the bed is <10% in 1990, up to 50% in 1997, then is reduced to 10% in 1999. The proportion of the River Wensum covered by a given sediment size is presented for the complete survey coverage in 1990 and 2004 in Table 5.6.

Table 5.6 Total proportions of the Wensum river bed covered in gravel and fine sediment. The total quantity of fines has decreased slightly in line with the site observations at Tatterford Common. The surveys were undertaken at different times of year (1990 surveys were late summer, 2004 surveys were conducted in winter) and this may explain some of the differences.

Year of Survey	% Gravel	% Sand	% Silt & clay	% total fines
1990 (RCS)	28	24.3	48.2	72.5
2004 (FA)	38	39	23.0	62.0

Overall levels of fine sediment have remained relatively constant (allowing for error), or declined slightly. Correspondingly the relative proportions of exposed gravel bed have increased. The main difference between the two surveys would appear to be a 50% decline in silt and clays. However, it is difficult to visually differentiate between sand and silt in many cases, and hence these values are likely to be indicative of a decrease in silt between surveys, though the absolute values remain uncertain. What is clear however is that the river bed of the Wensum is largely dominated by fine silts and sands, with pockets of cleaner gravel-substrate. The proportions of the different bed-substrate sizes tend to fluctuate markedly at some individual sites, whilst the overall pattern of deposition viewed at the catchment scale remains relatively stable in terms of location and total proportion of the bed; both conditions resulting primarily from the controlling influence of mill structures.

Figure 5.11 depicts the downstream proportion of fine sediments in association with the main controls on sedimentation ie the width: depth ratio; channel gradient and water surface gradient; and sediment ingress points. Some key patterns appear from this data:

- High width:depth ratios are associated with high proportions of fines overall but not in a consistent predictable fashion.
- High proportions of fine sediment are associated with ponded reaches, but in the headwaters, this is not a dominant control.
- In the headwater area, there is a high proportion of sand despite lower width:depth ratios and steeper gradients (though water gradients are unknown). However there is also a high frequency of sediment ingress points.

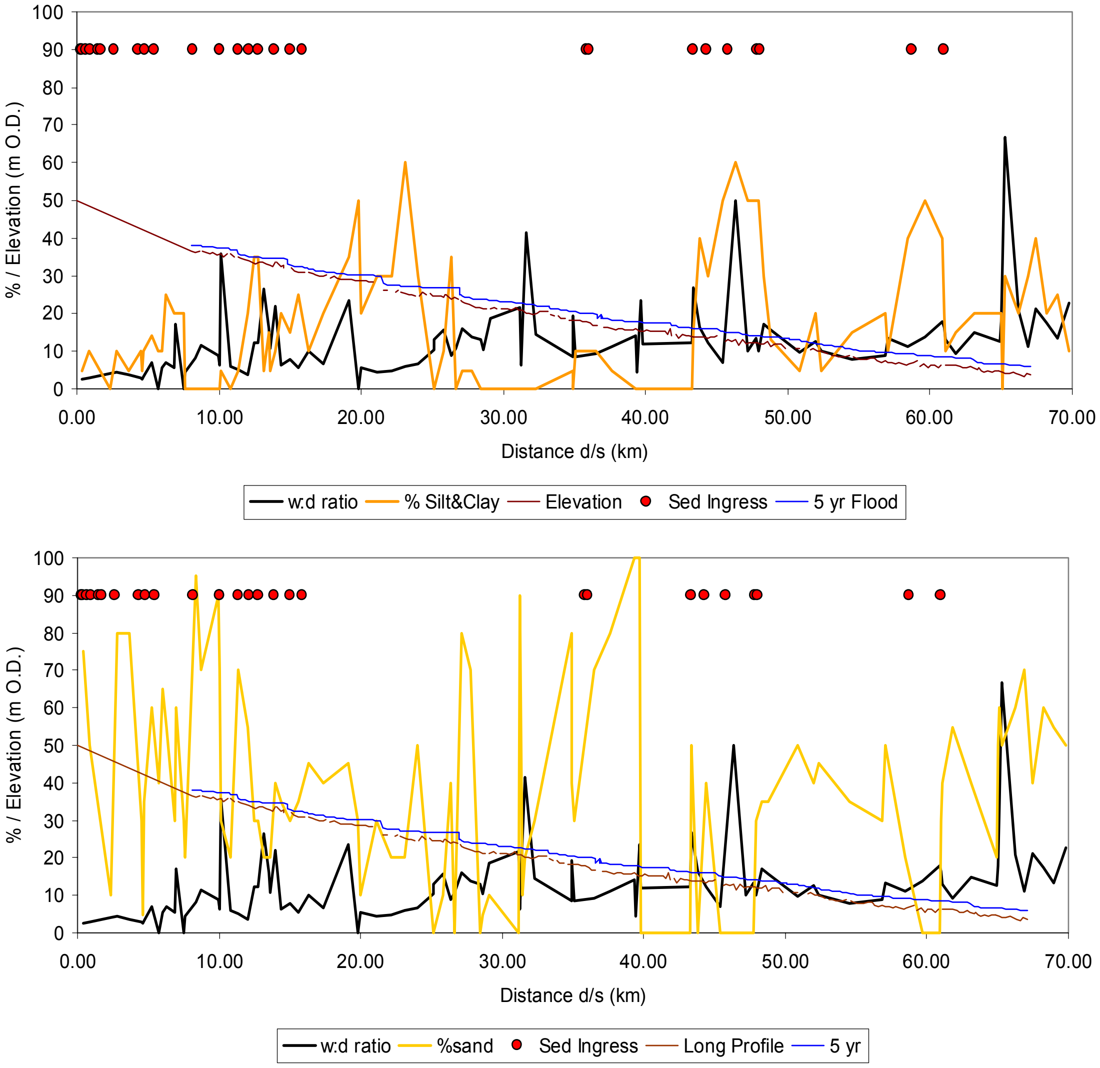

Figure 5.11 Fine sediment deposition on the stream bed in association with the main controls on sedimentation. Note the high proportion of sand in the upper 15km of the Wensum.

Field observations confirm that the headwater reaches of the Wensum appear to receive a high sand load. Figure 5.12: shows an ingress point cut into the upper Wensum in order to drain ponded surface water from an intensively cropped field. Similarly Boar and others (1994) reported gullying and soil erosion in the same headwater areas.

An important control on the trapping and storage of sediment on the river bed is the presence of extensive emergent and submerged macrophytes, indeed the two are related. Whilst macrophyte communities are a ubiquitous feature of chalk rivers and lowland channels (and one of the Annexe II habitats in the SAC designation), the presence of fine sediment and associated nutrients, in association with low flows and degraded morphology, create conditions where plant growth can choke the river channel and trap any incoming fines. During the summer, good examples of this type of control are found throughout the Wensum, and this is one of the principle reasons for weed cutting and desilting (Figure 5.13). While the long-term aim of management should be to expose and maintain the underlying gravel substrate, the sediment trapping properties of these macrophytes do not assist this process since although they trap fine sediment, their maintenance removes it, and vegetation die back also leads to release including high organic matter loads that could be deleterious to downstream reaches.

Particle size analysis of the fine sediments sampled along the Wensum from potential spawning habitats indicates that sand dominates the fines at these sites (Figure 5.14). There is a proportionately higher silt/clay content in the reaches around Great Ryburgh and downstream of the Wendling Beck, with more sandy substrates dominating the upper sites and at Lenwade. The median grainsize of the fine sediment on the bed surface is fine sand (0.5mm). Some 10-30% by dry weight of fine sediments is composed of decayed organic matter reflecting the productive growth of macrophytes within the channel.

Boar and others 1994 conducted a study of the fine sediments deposited upstream of mill weirs on the Wensum at Bintree, Hellesdon and Ringland. The data strongly suggested that at the two downstream sites (Hellesdon and Ringland) an increase in sand content had occurred which they associated with high flows in 1977, following the 1976 drought. This sedimentation was associated with a decrease in organic matter content and plant and invertebrate remains, suggesting that sedimentation by sands resulted in impoverished biological communities. An estimate of sedimentation rates from Ringland was 3cm per year over the period since dredging.

Figure 5:12 Fine sediment runoff into the upper Wensum showing a purpose dug channel to take field runoff into the river at reach W1064b (a), narrow strip between the river and the field systems W1064a (b), and evidence of sand deposits in the channel some 0.5km downstream W1063e (c).

Figure 5.13 Headwater channels choked with macrophytes and riparian plants, making an effective fine sediment trap (Reach W407). Gravel substrate is present in these reaches according to the 1990 RCS, but is dominated by fine sediments in the 2004 fluvial audit.

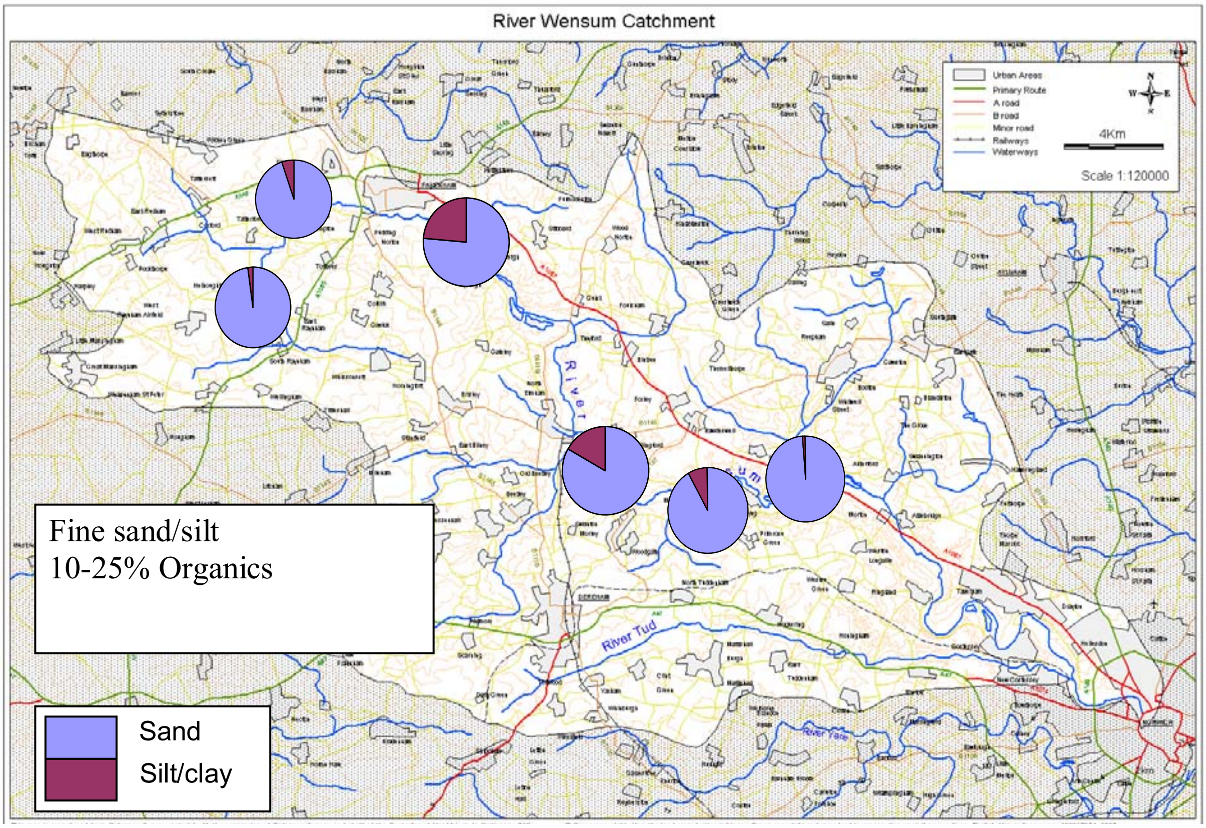

Figure 5.14 Fine sediment accumulation on the river bed and the dominant controls on sedimentation identified in the River Wensum.

5.2.4 Fine sediment storage in the spawning gravel habitat

A key element of chalk river sediments is the relatively large quantity of fine sediments stored within the gravels (Milan and others 2000, Whiting & Moog 2001). This results from the lack of flushing of the gravel framework due to the low stream power produced in these channels. The quantity of fine sediment stored within chalk river gravel beds is currently perceived to be of ecological significance in relation to the spawning requirements of salmonids, bullhead and lamprey. Furthermore, excessive fine sedimentation can obscure the gravel bed and create a relatively impoverished invertebrate fauna (Woods & Armitage 1999). Thus the estimation of the quantity of fine sediment stored within the gravel of the River Wensum is important both in terms of a potential source of fines itself but also as an indication of the quality of the spawning habitat.

A methodology was adopted based on that of Lambert & Walling (1988) in which a stilling basin is driven into the gravel bed; and the bed surface and subsurface are agitated; and the resulting fine sediment concentration sampled. The weight of fines (<1 mm) is then estimated from the concentration (g/l), volume of water in the stilling basin (l) and the area of the bed disturbed (m^2).

A total of 13 replicates were sampled at seven sites along the Wensum (Figure 5.15). At each site gravels were selected where conditions were appropriate for salmonid spawning. Values for surface fine sediment load in kgm^{-2} were variable between sites with no clear relationship related to channel width, slope or distance from source. Average values of fine sediment surface storage are 1.27kgm^{-2} (s.d. = 1.03 kgm^{-2}) whilst subsurface storage down to 10cm depth are much higher at 2.42 kgm^{-2} (s.d. 2.60 kgm^{-2}). These figures compare with average values of 0.25 kgm^{-2} (s.d. 0.13 kgm^{-2}) for surface and 0.41kgm^{-2} (s.d. 0.22 kgm^{-2}) for subsurface for the runoff dominated River Exe (Lambert & Walling 1988) and 1.04 kgm^{-2} (s.d 1.65 kgm^{-2}) for surface and 5.61 kgm^{-2} (s.d. 4.24 kgm^{-2}) for subsurface in the neighbouring catchment of the River Nar. This data supports the interpretation of the Wensum as a static river bed into which fine sediment accumulates in relatively large quantities compared with a runoff dominated stream with bed mobility and a large fine sediment load. The comparison with the River Nar suggests that the fine sediment tends to accumulate more on the surface and fewer fines are present within the gravel bed. An explanation for this may relate to higher flushing of fines from the surface gravels in the Nar, or the presence of sand seals at the surface which prevent the further ingress of fines into the bed.

Generally there is good correspondence between replicates indicating that between site differences are robust. Several points emerge from Figure 5.15:

1) The lowest storage of fines on the surface are associated with the upper reaches of the River Wensum.
2) The highest levels of surficial fine sediment storage occur at Bintree, Billingford and Lenwade Bridge where sand was clearly present on the riffle surface.
3) The highest levels of subsurface fine sediment storage occur at Bintree, and at Lenwade Bridge and Lyng.

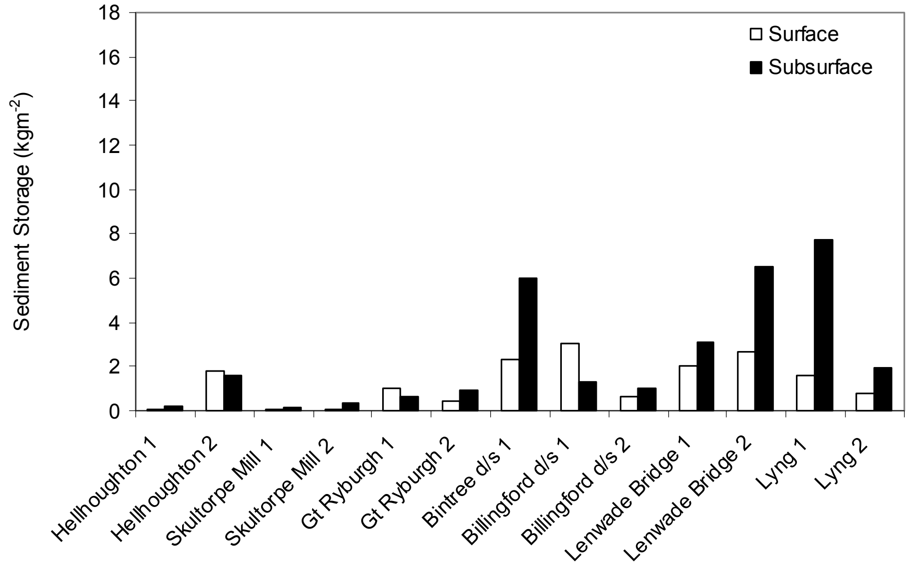

Figure 5.15 Fine sediment storage on the bed surface and within potential spawning gravels in the River Wensum. Values are typically 3 times higher than those found in steeper upland runoff dominated rivers. (list grid references for sample sites)

There is a weak correlation between field measurements of bankfull channel width and surface fine sediment accumulation, but less so for sub-surface fine sediment accumulation. There is no correspondence with shear stress at each site. There is a weak increase in fine sediment loads with distance downstream, suggesting that it is sediment supply that is controlling the magnitude of the accumulation, modified by local flow conditions. The downstream site at Lyng was regarded as a good spawning habitat, yet retains among the highest levels of subsurface fines. The surface was relatively clear of fines at this site, but clearly this is no evidence for subsurface fine content.

An important observation is that the river bed is a store for fine sediments. Estimates of potential fine sediment release from a $100m^2$ of riffle surface that might be gravel cleaned range from 18 – 929 kg. Storage of surface fines in pool and glide habitats (and presumably also in impounded reaches) are likely to be significantly higher, hence the volume of fine sediment on and within the bed of the River Wensum is a significant potential source of fines to downstream reaches.

5.3 Classification of River Wensum sediment system

The status of the River Wensum reaches identified by fluvial audit were assessed in terms of their function as either a source or storage reach for fine sediments. Note that reaches can be defined as both, in that storage of fines in one reach will provide a source of fines to downstream reaches. The criteria used in the classification of sediment source were:

- The percentage of fine sediment on the river bed surface.
- The total number of sediment ingress points in the reach.
- The proportion of bank erosion in a reach.

The criteria used in the classification of sediment storage (sinks) were:

- The percentage of fine sediment on the river bed surface.
- The proportion of each reach area occupied by fine sediment berms.

Each criterion was weighted such that a score reflected the total sum of the criteria multiplied by their weighting. The table of scores and weightings applied to all Multi-Criteria Analysis are given in Appendix 2 and the scores for each reach are given in Table 6.2. The MCA model was then run on the fluvial audit database and visualised in the GIS. Maps of sediment source index and sediment storage index are given in Sediment Source Maps 1-3 and Sediment Storage Maps 1-3. These maps are included as Appendix 3.

Those reaches with the highest scores were indicative of reaches that were functioning as a sediment store (sink) or sediment source. In practice only those reaches with high scores (coloured blue) should be considered. The classification identifies sediment source reaches and sediment storage at locations throughout the length of the River Wensum. There is no clear geomorphic reason for the distribution of sediment source and storage sites along the Wensum, and since the mobile load is fine sediment, it is the hydraulic controls that influence the patterns of accumulation. The headwaters of the River Wensum are clearly identified as a sediment source area largely due to the ingress points, sandy bed and presence of macrophytes that choke the channel during the summer (Boar and others 1994, Econ 1999). Silt ingress and fine sediment stored on the river bed account for the relatively high frequency of sediment source reaches identified upstream of Fakenham. Sediment source areas downstream tend to be associated with high proportions of sediment on the river bed, in these cases controlled by mill weirs (eg Gt Ryburgh, Swanton Morley and Elsing mills). Other mill ponded reaches are not clearly defined as sediment sources, but this is considered to result from not including the ‘Not Visible’ (NV) category in the classification. The ‘not visible’ category is recorded in the field surveys where features are obscured. If NV is included then the remaining mill ponded reaches become classified as sediment sources/sink zones within the channel.

6 Capacity for natural recovery

The results of this analysis for the River Wensum support the view that the form and distribution of coarse gravel bed forms of the river result from:

1) Inherited ‘relic’ planform, gravel bed topography and sedimentology arising from glacial and postglacial river processes that were characterised by steeper valley gradients (sea level was far lower) and higher runoff compared with present (and future) conditions.
2) A long history of channel modifications that have altered the channel planform, cross-section and bed materials and which persist in the absence of coarse sediment supply and bed mobility.
3) Local scour and short-distance gravel transport associated with local increases in bed and valley gradient (eg downstream of mill weirs), flow acceleration through channel constrictions (eg fallen debris, bridges, narrowed channels), strongly 3-dimensional flows that cause spatially discrete zones of scour (eg scour on outer banks of meanders in the headwaters particularly).

The main findings of the geomorphological analysis clearly demonstrate that the mobile sediment load is restricted to coarse sands, silts and clays, with only local mobility of fine gravels. Turbidity records demonstrate that the fine sediments are supply-limited during flood events (they peak before the peak discharge), yet the field assessment demonstrates that catchment sources exist and can potentially transport fine sediment directly into the river via the road and field drainage networks. Bank erosion is not an important source, a fact confirmed by the lack of lateral channel migration evident over the past 100 years. The dominant controls on fine sediment transport are therefore hydraulic. These include mill weirs, but also the over-widened and over deepened nature of many reaches of the Wensum that, in association with low gradient water surface slopes, create extensive areas of low sediment transport capacity.

The extent of over-widening can be assessed using locally derived regime relationships between catchment area and bankfull discharge dimensions. This empirical approach is sensitive to the assessment of a channel as being un-modified and in a natural state. However, by using local catchments (including some data from the Wensum), it is possible to create a model of bankfull dimensions, and then plot the actual Wensum measurements against the model. Figure 5.16 presents the bankfull width and depth values for the River Wensum downstream as far as the confluence of the Blackwater (Lenwade). The existing channel widths around the confluence of the Wensum and Tat are close to that predicted, suggesting that the modifications made are primarily to the depth of the channel. This appears to be the case for the reach of the Wensum just upstream of the confluence with the Tat, whereas the reach downstream has similar width and depth to that predicted to be natural. Downstream of the Tat confluence, the channel widths at bankfull are much larger than predicted while the bankfull depths vary – with mill ponds typically recording over-deepening, and other reaches with gravel beds, recording lower than expected depths. This latter observation is not unexpected since bankfull depths are naturally highly variable about a mean value.

The accumulation of silts, sands and the growth of vegetation provide the main method of self-recovery of modified channel dimensions. Figure 5.17 shows an example of how in some areas the channel widths have been reduced by berm development back to values close to predicted. Lateral sediment accumulation is extensive in some areas along the Wensum where the channels have been widened. Boar and others (1994) report the recovery of the Wensum at Gogg's Mill, Fakenham which was removed in 1957 by the East Suffolk and North Norfolk River Board. When the mill pond existed, channel bankfull widths were around 20m, today the width is between 4 and 6 m. Boar and others (1994) conclude in their study of channel narrowing, that the middle and lower reaches of Wensum, outside the influence of the mill ponds, are still around 5-10 metres wider than predicted from meander bend geometry. The empirical results presented in Figure 5.16 suggest the value is closer to 4 -7m wider. Maintenance in the lower reaches may explain why silt accumulation has failed to narrow the river still further.

It is important to recognise that although the channel width may adjust, the absence of gravels means that the bed levels are unlikely to recover, hence the channel becomes floored by fine sediments, or the channel remains narrow and deep. An important conclusion therefore is that wherever possible channel restoration should seek to redress the deepening of the river by past modifications, through the reintroduction of gravels.

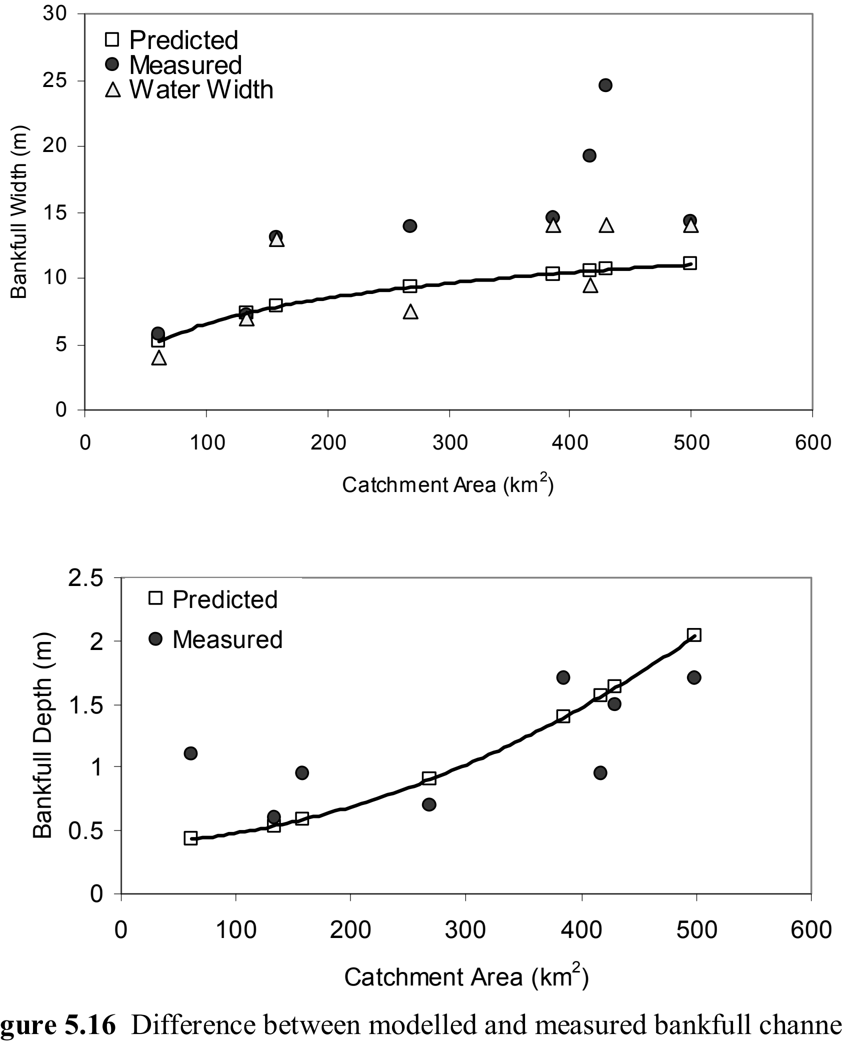

Figure 5.16 Difference between modelled and measured bankfull channel properties based on semi-natural reaches of the River Nar and Wensum. Source: Harvey 1967 and Goff 2004 – Newson pers comm.).

Figure 5.17 An example of width recovery by deposition of fine sediments along the margins of the over-widened channel (reach W510). Yellow denotes modified bankfull width, white denotes recovering channel width.

The sediment transport processes reported in the River Wensum make the system:

- Highly sensitive to any form of channel modification since what is removed is unlikely to re-form through natural processes.
- Highly sensitive to increases in fine sediment loads since the stable bed sediments will tend to accumulate fines without being flushed (this is confirmed to some extent by the reported high levels of fines in chalk river sediments; Acornley & Sear, 1999; Milan and others 2000) and the presence of over-widened and deepened channels and mill weirs which create loci for fine sediment storage.
- Unpredictable in terms of channel morphology and sedimentology with strong local control on channel form. The morphology is therefore not amenable to “textbook” restoration designs or importation of existing channel classifications but requires a local restoration vision based on understanding processes and modification history.

Conclusions

- The gravel bed and morphology (where semi-natural) are among the highest value conservation features of the River Wensum.
- The mill weirs and associated ponding have made the largest and longest-lasting impact on sediment transport and channel hydraulics. Management of these structures is an essential part of restoring natural physical processes to the river system and floodplain.
- Fine sediment production from the catchment surface is higher than natural. The supply of fines into a channel with a modified sediment transport regime will lead to

net sediment storage. However, the accumulation of fine sediments in reaches where the channel is over-widened and NOT deepened, represents a cost effective method of channel recovery, and probably at higher rates than would naturally occur.

7 The development of the river restoration vision and strategy

The vision for the restoration of the river needs to be based on a set of three scientifically justifiable principles:

1) Restoration of natural process rates.
2) Restoration of natural processes where these are missing.
3) Restoration of natural form where this has been damaged by past modification since the river is only able to adjust through fine sediment deposition.

It is recognised from the outset that the restoration of forms and processes should be based on those that can be sustained under current and future climate and sea level conditions. It should also be recognised that this report deals only with the functioning of the geomorphological processes; the same principles apply to hydrological, nutrient and biological processes.

The significance of the preceding sections of this reportlies in providing the scientific justification for recognising that the channel and floodplain of the River Wensum has undergone significant transformations in morphology, process dominance and resulting physical habitat. Furthermore, many of the features of the current landscape can only be understood in relation to the sequence of past processes. It is also important to understand the large scale causation of valley and river morphology since this helps to define what is ‘natural’ and therefore what is an appropriate definition of “reference condition” for the different river types represented within the Wensum catchment. Clearly, the importance of past climatic changes in creating the larger scale morphology of the River Wensum and its valley provide the context for the management of the channel into an era of predicted climate change and sea level rise.

The general implications of the geomorphological analysis of the River Wensum highlight the largely relic nature of the valley sediments, planform and gravel bed topography. The inability of the current river channel to actively supply coarse material from either catchment sources, bank erosion or mobility and flux of bed material, results in a situation where the river geomorphology and coarse substrate are highly sensitive to modification. The combination of historical topographic surveys, channel maintenance records and contemporary surveys of the channel substrate and morphology support this assessment and demonstrate that the river can be viewed as an essentially static channel form and substrate over which catchment-derived sand, silt and clay passes, accumulating only in areas of relatively low velocity. An additional proportion of the fine load is organic, with a likely source being decaying macrophytes and invertebrate faecal pellets. Restoration of natural processes and form must be viewed within this context.

The sediment transport analysis has demonstrated how the channel is linked to the catchment surface through road, footpath and drainage networks. The assessment of modifications has demonstrated that the Wensum is largely modified, but with some areas of low documented modification. Restoration of the River Wensum must recognise the following constraints:

1) River processes will not replace dredged gravel substrates.
2) River processes will not create extensive coarse gravel features.
3) Fine sediment is the only mobile component of the sediment system.
4) The Wensum is sensitive to increases in fine sediment loads due to a natural inability to flush fines.
5) Channel planform, long profile, cross-section form and connectivity with the floodplain are relics of past processes and will not recover to pre-disturbance states.
6) Natural processes of recovery will be dominated by fine sediment deposition and growth of aquatic vegetation.
7) The hydrological network of the River Wensum should be viewed as including roads and associated drainage networks as well as the sequence of field drainage systems. Management of these is as important to the restoration of the River Wensum as is manipulation of the river network.

An important element of the restoration vision is based on assessing the extent to which the current channel diverges from the natural condition. Defining “naturalness” is therefore an important element of the restoration process since it provides the reference conditions. Reference conditions may form the basis of channel designs, and the baseline against which to monitor the effectivness of the restoration.

7.1 Defining channel naturalness and reference condition for the River Wensum

The European Committee for Standardisation (CEN 2003) lists reference conditions for hydromorphological quality in rivers as:

- reflecting totally, or nearly totally, undisturbed conditions;
- lacking any artificial instream and bank structures that disrupt natural hydromorphological processes, and/or unaffected by any such structures outside the site;
- bed and bank composed of natural materials;
- planform and river profile: not modified by human activities;
- lateral connectivity and freedom of lateral movement: lacking any structural modification that hinders the flow of water between the channel and the floodplain, or prevents the migration of a channel across the floodplain;
- lacking any instream structural works that affect the natural movement of sediment, water and biota;
- having adjacent natural vegetation appropriate to the type and geographical location of the channel.

When considered in accordance with these definitions, the River Wensum is NOT in good hydromorphological quality. However, some reaches may be closer to these hallmarks of naturalness than others. The vision for restoration should therefore aim to move the River Wensum towards this condition, within the constraints of flood risk management where built environment is at risk, and progressively as funds permit. It is equally important that any restoration does not make the current status any worse.

The CEN definitions are generic. What is necessary is to define naturalness for the local conditions in the Wensum catchment. Appendix 4 details the process through which this has been undertaken for the broad river type on the Wensum; groundwater dominated rivers flowing from chalk geology with overlying glacial deposits. Two sources of information have been used to define a natural vision for these channel types:

1) Scientific literature where available from semi-natural or natural rivers of similar type.
2) River Habitat Survey data for semi-natural reference sites of similar type.

The physical attributes derived from these data sources have been combined into a table for each river type. Not all values are available from existing data. Those that are available have been used according to the naturalness index in the MCA tables in Appendix 2. It is recognised that the attributes, scores and weights are subjective. The MCA process enables discussion and modification of these according to expert or local understanding and could form the basis of decision support and stakeholder involvement. For example, the results of the MCA for reach W550 propose reconnection of river to reedbed. Local knowledge (Dryden pers com) indicates that this may not be the best option since the reedbed is spring fed and water levels can be adjusted to the desired level by means of a sluice on the drain at the downstream end of the reedbed, and nutrient levels are an order of magnitude lower in the reedbed water than in the river – which benefits the fen meadow community which occurs in a mosaic within the reedbed. Such local information is needed before specific plans are implemented.

The naturalness index was derived for each reach identified by fluvial audit. The lower the index score, the higher the naturalness of the reach as defined by the attributes used. The modification index was also derived for each reach based on a wide range of field based and secondary derived attributes that indicated physical modification of the channel form and sediment regime. As with the naturalness index, the lower the score, the less the level of modification to the river profile. The datasets for modification stem from a number of sources and measures and therefore judgement was used to allocate the different types of intervention to a score, which was then combined with other variables to generate the overall index value. The existing modification index was enhanced by including two other categories; presence of ponded flow upstream of structures and > 80% bed cover by macrophytes. The naturalness index and modification index were then overlaid in the GIS and both visualised. The resulting reaches are coloured according to the degree of naturalness and modification. This provides a set of potential classes for each reach – in principle similar to the RHS Physical Quality Objectives (Walker and others 2002), only in this case derived from science-based and locally applicable datasets. Figure 6.1 illustrates the potential classes arising from the combination of naturalness and modification indices.

	0 Natural	1 Predominantly natural	2 Partially natural	3 Practically Un-natural	4 Un-Natural
0 Unmodified	Natural	Semi-Natural	Damaged	Damaged	Damaged
1 Predominantly Unmodified	Semi-Natural	Semi Natural	Damaged	Damaged	Damaged
2 Obviously Modified	Recovered	Recovering	Degraded	Degraded	Degraded
3 Significantly Modified	Recovered	Recovering	Degraded	Severely Degraded	Severely Degraded
4 Severely Modified	Recovered	Recovering	Degraded	Severely Degraded	Artificial

Figure 6.1 Classification of reach types arising from the combination of Modification and Naturalness indices.

Each reach class can be allocated a management action required to move the river towards an improved condition. In the simplest case of a natural river reach the action would be to protect and monitor status. For the artificial river reach it is most likely a case of do nothing as there is very little that can be achieved. Figure 6.2 details the management options for each river class. These form the basis for the restoration vision for the River Wensum. Definitions of the terms used are given in Table 6.1. The final element of the vision is to recognise that maximum gain in terms of restoration is achieved by building out from the best sites, rather than attempting to improve the mediocre sites.

	0 Natural	1 Predominantly natural	2 Partially natural	3 Practically Un-natural	4 Un-Natural
0 Unmodified	Protect & Monitor	Protect & Monitor	Assist natural Recovery	Restoration	Restoration
1 Predominantly Unmodified	Protect & monitor	Protect & Monitor	Assist natural Recovery	Restoration	Restoration
2 Obviously Modified	Conserve & Monitor	Assist natural Recovery	Rehabilitation	Rehabilitation	Enhancement
3 Significantly Modified	Conserve & Monitor	Assist natural Recovery	Rehabilitation	Rehabilitation	Enhancement
4 Severely Modified	Conserve & Monitor	Assist natural Recovery	Rehabilitation	Rehabilitation	HMWB

Figure 6.2 Management action associated with each reach class. Definitions of the terms used are given in Table 6.1. (HMWB – Highly Modified Water Body).

Table 6.1 Definition of terms used in Figure 6.2. Typically, costs rise towards the top of the table.

Term	Definition
Restoration	Restoration of channel processes and forms to pre-disturbance conditions.
Rehabilitation	Physical modification to the river form to re-create physical habitats (eg re-meandering, riffle installation, bed level raising).
Enhancement	Addition of structural features to improve physical habitat diversity (eg narrowing, woody debris).
Protect & monitor	Afford legal protection to the site and monitor for change in status. Given that the site has legal protection (SSSI/SAC), monitor to ensure that the status is maintained and take action if required.
Assisted natural recovery	Amplification of existing processes to encourage recreation of physical habitats (eg encouraging berm formation to narrow channel, removal of bank revetment to create sediment supply).
Conserve	Protect site against further degradation not necessarily with legal statute.

What may be helpful to river managers is a typology of river restoration approaches that provides them with a means of clearly communicating their actions to a wider stakeholder community. Figure 6.3 below presents some of the typical options in a simple matrix of restoration approaches. These are defined in terms of:

Active restoration – physical creation of forms or removal of structures to improve degraded ecosystems.
Passive restoration –physical manipulation of flow and sediment transport regime to create physical habitat and to improve degraded ecosystems.
Form-mimicry – the re-creation of physical habitat features without reference to the processes required to create them.
Process-based restoration – the use of physical processes to restore degraded physical habitats to a more natural form.

	Active	**Passive**
Form-mimicry	Riffle recreation Re-meandering	Gravel augmentation which then is moulded by river flows into bed features (riffles)
Process-based	Mill weir removal – restores sediment connectivity and hydraulic gradient Re-occupation of an old channel course	Reduction in catchment sediment supply Management of flow regime (flow re-naturalisation)

Figure 6.3 A typology of river restoration options.

Use of such a typology enables river managers to clearly identify where they are replacing degraded habitats or introducing new habitats without consideration of the sustaining river processes, or where they are attempting to restore the processes with the intention of recreating better physical habitats. These help to define the goals of each project and manage expectations. Thus a riffle creation project without reference to fine sedimentation, may create a riffle looking feature, but the functionality of that feature may be restricted by siltation to providing a local patch of faster water over a gravelly substrate and an increase in upstream pool depth. The goal should be for restoration of natural processes wherever possible.

7.2 A classification of management options for the River Wensum

Table 6.2 provides a reach by reach classification according to the criteria outlined in Figures 6.1 and 6.2. The classification has been checked against an independent classification in the River Wensum fluvial audit, and further verified by assessment against another independent dataset, and against expert assessment of the field photographs. The classification process is able to distinguish natural to modified reaches, verified from three different sources. The MCA analysis should not be seen as static, but should be modified as more information is generated, and can be subject to expert consultation and modification. Thus the weightings and values can be changed according to new or local knowledge in order to fit the classification more closely to the river catchment under study. The weightings chosen are based on expert geomorphologists' experience in the absence of statistically valid relationships between the variables to define weights.

Options for restoration are also given in Table 6.2. These are based on an assessment of the main contributory indices to the naturalness scores and modification scores. Each reach was also checked against the photographs and map-based information on the GIS. The reach status and reach management classes are provided in map formats in Maps 1-3 (Naturalness and Modification) and Maps 1-3 (Reach management type) and all the data are accessible as a layer within the GIS (Appendix 3).

The options for restoration are broad and do not define the precise methods and techniques for activities, such as restoration, levels for weir reduction, timescales for reduced maintenance; these are beyond the scope of this report. A separate design specification programme is needed to establish the appropriate approaches for each site. Where the strategy is examined by the ECON (1999) report this should be referred to directly and the details of these proposals are not repeated in this document. The ECON report, with considered the river from the perspective of fisheries, contains extensive rehabilitation information and summary data on the state of the Wensum. The current survey does not attempt to establish a programme of work or a specific plan for any of the proposed restoration options, which is beyond the scope of the fluvial audit. However, when considered together with the GIS, Table 6.2 provides a basis for developing more detailed schemes.

The prioritising of the restoration options should be guided by catchment scale requirements:

1) Establish a programme for treating the sediment ingress problems identified by this report prior to any physical habitat restoration/rehabilitation or enhancements except where these form part of the sediment source control.
2) Set in place a condition monitoring plan for all semi-natural/natural and recovering reaches.
3) Prioritise the restoration/rehabilitation/enhancement on the basis of linking existing natural/semi-natural reaches first.
4) Seek to improve those reaches closest to semi-natural conditions.
5) Work from upstream to downstream within the catchment. The modelling study supports the option for upstream restoration reducing flood peaks in the lower reaches through attenuation of the hydrograph. Furthermore, as upstream reaches improve, the drift of biota will help colonise the downstream reaches.