Chapter 19

EFFECTS OF GRAVEL EXTRACTION ON STABILITY OF GRAVEL-BED RIVERS: THE WOOLER WATER, NORTHUMBERLAND, UK

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ABSTRACT

Commercial extraction of gravel for aggregates is a global phenomenon that has affected many piedmont gravel-bed rivers in the UK. Although licenses for commercial extraction are now carefully controlled, some are viable until 2042 AD. Geomorphological effects of gravel mining are reviewed and extended using information collected from northeast England and, in particular, the Wooler Water in Northumberland, UK. During the past 50 years, gravel extraction has led to incision of up to 9 m, and the metamorphosis of channel planform from a laterally active wandering gravel-bed river to a largely single-thread, sinuous channel. The sequencing of gravel extraction over the fifty-year period is shown to influence channel planform development, though the majority of channel change occurs where extraction coincides with high-magnitude, infrequent flood events. Effects of gravel extraction are considered in terms of flow strength, perimeter erodibility and relative sediment supply. The instability of gravel extraction sites is discussed in terms of river management and geomorphological interpretation.

19.1 INTRODUCTION

River beds have historically been an attractive source of gravel supply for building aggregate and road surfaces where suitable rivers existed close to the point of use. River gravels are generally clean, can be relatively well sorted, are easy to extract, require little processing, and are periodically replaced from upstream during high river flows. Commercial gravel extraction from river beds is a global phenomenon (Page & Heerdegen, 1985; Erskine *et al.* 1985, Lagasse *et al.* 1980) and was, until recently, widespread in the UK (Newton, 1971; Newson & Leeks, 1986).

Even so, comparatively little has been written on the geomorphological impacts of direct river extraction (Newson & Leeks, 1986). Table 19.1 presents documentation of the kinds of impacts that can be expected during and following gravel extraction. In at least two of the cases cited, much of the impact analysis was based on modeling without empirical confirmation.

Table 19.1. Documented impacts of gravel extraction.

Source	Date	Extraction purpose	Method of research	River	Impacts
Kira	1972	Aggregates	Topographic survey	Several (Japan)	Degradation, loss of habitat
Kostourkov	1972	Aggregates	Topographic survey	Several (Bulgaria)	Degradation
Lagasse *et al.*	1980	Aggregates	Topographic survey	San Juan Creek	Degradation
Lagasse *et al.*	1980	Aggregates	Modeling/sediment re-survey	Mississippi (USA)	Planform change, disruption & fining of armor layer
Galay	1983	Aggregates	Topographic re-survey	Several (USA)	Degradation
Hay	1985	Gold mining	Literature review / modeling	Grey River (New Zealand)	Bank erosion of tailings
Page & Heerdegen	1985	Aggregates	Topographic survey	Manawatu River (New Zealand)	Degradation, planform stability
Erskine *et al.*	1985	Aggregates	Modeling sediment transport	Hunter River (Australia)	Disruption of armor layer
Newson & Leeks	1986	Aggregates	Sediment survey modeling	Tywi (Wales)	Disruption & fining of armor layer, habitat degradation

Documented impacts include:

- disruption of sediment continuity,
- channel degradation,
- destruction of in-channel structures,
- nick-point recession up tributaries following main river degradation,
- increased levels of downstream turbidity,
- planform changes (causing both stability and instability), and
- disruption of bed sedimentology.

Obviously, the impact of gravel mining on the stability of river planform is complex. Lagasse *et al.* (1980) and Newson and Leeks, (1986) identified increased in-channel planform instability, though channel boundaries showed little change, and concluded that natural catchment processes often obscured the impacts of extraction on river planform. Page and Heerdegen (1985) similarly could not distinguish between rates of channel change resulting from gravel mining or large flood events in the Manwatu River. Incision of the river bed as a result of gravel extraction often continues long after the period of mining and may initiate problems associated with tributary rejuvenation (Galay, 1983). While armoring of the bed may act to stabilize the rate of degradation, as disruption of the armor layer occurs during extraction this may not occur until sediment transport decreases from active, upstream nick points.

The need to account for the operation of gravel extraction at sites in a river is clearly important, since the tendency for extraction sites to be both vertically and laterally unstable long after production has ceased gives cause for concern if the mining activity is not recognized prior to geomorphological analysis. Recognizing the history of extraction at a site can help in the subsequent management of the river, since gravel extraction sites are often associated with erosion or deposition problems which require expensive investment in bed and bank protection by the relevant river management authority (Lane, 1947; Sear & Newson, 1991). This chapter draws on examples of gravel mining from the northeast England, in particular the Wooler Water, to identify the nature, scale and rates of morphological impact caused by commercial gravel extraction in piedmont gravel-bed rivers.

19.2 GRAVEL EXTRACTION

The northeast region of England has a long history of gravel extraction from rivers for commercial and industrial uses (Newton, 1971). The main rivers of the region have wandering gravel-bed morphologies, characterized by zones of stable single-thread channel interspersed with areas of relative planform instability and gravel deposition (Macklin & Lewin, 1989; Sear, 1992). Sediments are characterized by poorly sorted sands and gravels with boulders not uncommon (Hall, 1964; Sear, 1992). The south part of the region is characterized by Namurian sandstones and limestones, with locally significant igneous intrusions, while in the north the Cheviot massif is dominated by granite, andesites and Lower Old Red Sandstone (Hall, 1964; Tipping, 1994). The drift geology of the region is dominated by thick deposits of glacial boulder clay with glacial sands and gravels providing valley fills. Basin-wide vertical and lateral instability over the Holocene has produced a suite of alluvial terraces of reworked glacial sands and gravels (Peel, 1941; Tipping, 1994). Gravel extraction has been important as a source of aggregates within the region, and has resulted in many rivers being mined commercially (Figure 19.1).

Originally, land and water authorities in the UK viewed river-bed gravel working as advantageous to land drainage and the "extension of direct winning of gravel from river beds was to be encouraged as it saves valuable farmland" (Ministry of Housing & Local Government, 1952). The volumes of gravel extracted from river beds increased during and after World War II, reaching a peak in the mid 1960s (Newton, 1971). During this period, the combination of severe flooding and intensive commercial extraction resulted in significant

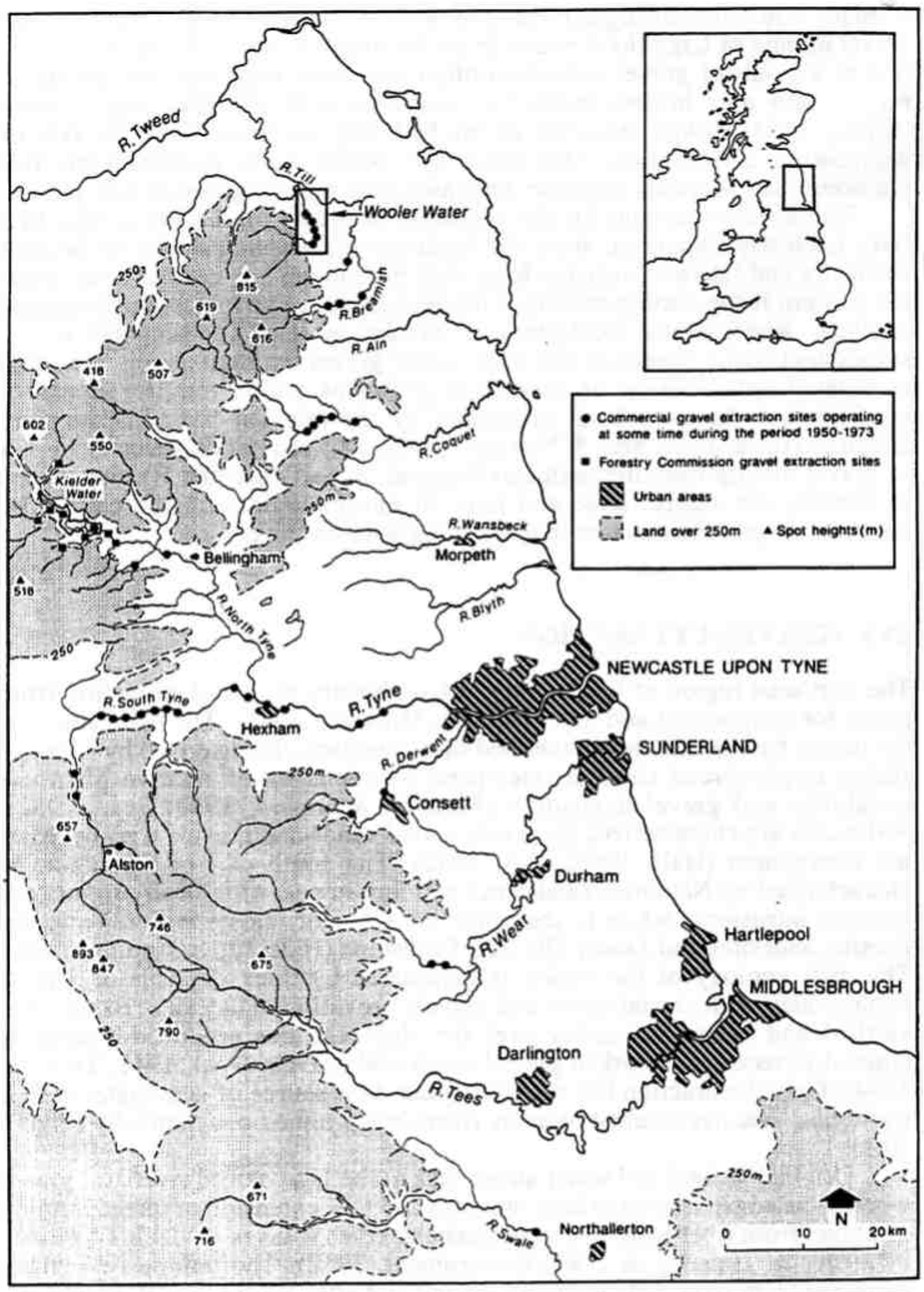


Figure 19.1. Gravel extraction sites located in northeast England.

river instability and loss of salmon spawning gravels. This significantly altered the attitude of land and water management bodies to the extent that today, new proposals for river-bed gravel extraction are refused on the principle that significant environmental degradation will result. Nevertheless, licenses to extract gravel from the river bed still exist on many UK gravel-bed rivers, some until 2042 AD.

Figure 19.1 illustrates the extent of gravel extraction in the northeast region during the past 50 years when reliable records are available. Widespread commercial activity has occurred on many of the region's main rivers, although not all sites were operational at the same time. The Tyne was a major gravel source during the post-war period, producing 75% of the gravel for the county of Northumberland in 1960. Though gravel extraction on the Tyne ceased in the early 1970s, commercial operations continued into the late 1970s and early 1980s on the Rivers Wear, Swale, Coquet and Wooler Water.

19.3 WOOLER WATER FIELD AREA

The Wooler Water, which provides a case study here, is a tributary of the River Till, and in turn the Tweed. It rises as the Harthope Burn, above 600 m on the eastern slopes of The Cheviot (Figure 19.2). The Harthope Burn follows a steep, fault-directed course to the northeast before joining the Carey Burn where it diverts first east, then north through the study area in the reach just upstream of the town of Wooler. The bedrock is rarely exposed and is covered by a variable depth of drift deposits. Till, soliflucted head and fluvioglacial sediments provided a ready source for Holocene fluvial reworking which has created a broad terrace downstream of Coldgate Mill; the Haugh Head terrace which contains 10 m of sands and gravels tentatively dated to the Loch Lomond Stadial (Tipping, 1994). Incision of at least 8 m following the formation of this terrace was followed by a period of relative stability characterized by the development of valley peat. At around 3900 - 4200 BP a large alluvial phase resulted in the deposition of coarse sands and gravels of the Earle Mill terrace (Tipping, 1994). A further two terraces below the Earle Mill terrace level are identified by Tipping (1994); however the origin of these is subject to some debate and will be discussed in the context of gravel extraction. Relevant catchment information is given in Table 19.2, while further detailed information may be found in Milne (1982a) and Harrison and Tipping (1994).

On the Wooler Water, gravel extraction occurred at four separate but contiguous working areas covering a reach 2.5 km in length upstream from the A697 Wooler road bridge. The earliest workings were in Reach 1 (Figure 19.2) upstream of the bridge where commercial extraction started in the mid 1930s but had been preceded by small scale local extractions. This working area was severely affected by flooding in August 1948 and October 1949. The channel became three times wider, new channels were created, bankside trees were torn down, and fields were strewn with boulders (Archer, 1992). Prolonged remedial work by the River Board probably marked an end to this period of extraction. Figure 19.2 illustrates how the works were extended upstream beyond Haugh Head ford over three decades. During the period of extraction, successive flood events resulted in significant channel changes. This eventually led to cessation of commercial extraction from the river bed in 1970, although channel-side gravels were mined until 1973.

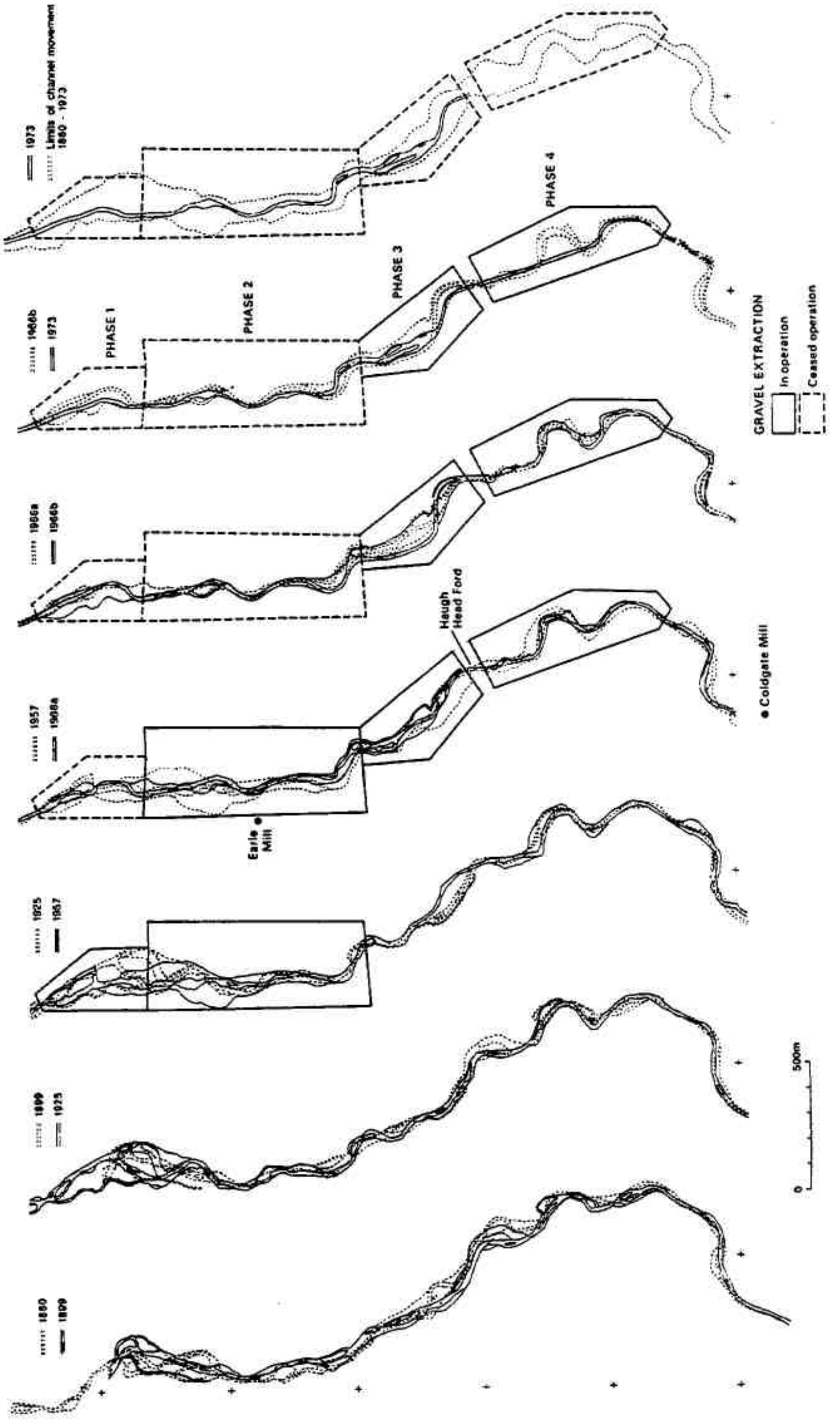


Figure 19.2. Location and 128 year time sequence of channel planform changes on the Wooler Water.

Table 19.2. Catchment characteristics, Wooler Water, Northumberland UK.

Feature	Characteristics
Catchment Area	52.5 km^2
Slope	0.060
Stream Length	26 km
D_{16}, D_{50}, D_{84}	80 mm, 152 mm, 215 mm
Geology	Woolhope Granite, Hedgehope granodiorite, Andesite, Boulder clay, Fluvioglacial outwash gravels, alluvial sands & gravels, peat
Land uses	Unimproved moorland, improved moorland, pasture, gravel extraction

19.4 STUDY METHODS

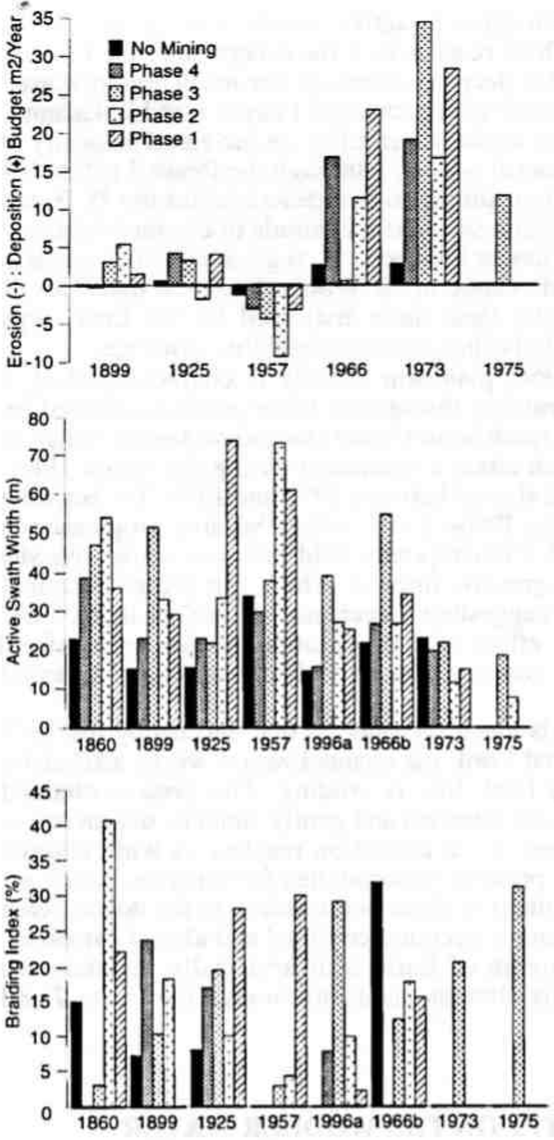
In order to assess the rates and typology of channel response to gravel extraction on the Wooler Water, historical data were supplemented by recent surveys to provide information for periods prior to, during, and after extraction. The phasing of extraction on the Wooler Water over a period of 30 years provides an opportunity for ergodic analysis of channel response to extraction, though changes at the lower reaches will undoubtedly have been affected by upstream extraction. In order to establish planform changes, historic maps were combined with more recent aerial photographs and channel surveys to produce a sequence of channel planform change. Using the technique deployed by Gurnell *et al.* (1994), the data series was digitized using SPANS MAP GIS software, and each series overlaid at the same scale using specified control points. The whole series was overlaid and the total channel swath divided into polygons of 200 m downstream spacing. Within these polygons, changes in channel width and areas of erosion and deposition of the floodplain were calculated. Gurnell *et al.* (1994) have established error margins for this technique at ± 5 m lateral channel change while Ferguson (1977) and Lawler (1993) caution the interpretation of results generated on this basis as minimum values of change. In-channel gravel shoaling was not incorporated in the values of erosion-and-deposition as there is considerable uncertainty in depicting shoaling, which may change between survey days within one survey period as well as between survey dates. Nevertheless, a value for braiding index was calculated to distinguish between areas of single- and multi-thread channel.

Vertical instability was identified from re-surveys of the longitudinal profile and cross section of the Wooler Water, conducted by the Northumbrian Rivers Authority in 1966, the Northumbrian Water Authority in 1973 and 1975, and a re-survey made in 1995. Each survey was digitized and adjusted to a single scale for analysis. In the case of the 1995 re-survey, positive identification of the earlier survey benchmarks was made and the centerline of the wetted channel used to establish the longitudinal profile, following the procedures used by the earlier surveyors. Additional information on vertical instability was collected from National Rivers Authority records and photographs.

19.5 PLANFORM CHANGE ON THE WOOLER WATER

Planform instability is a feature of piedmont gravel-bed rivers and is a response to a high rate of sediment supply from the upland catchment, balanced against a reduction in transport capacity as the channel slope decreases (Schumm, 1977). The Wooler Water is no exception and is characterized throughout the pre-mining period 1867-1925 by a wandering course, with a tendency to switch from meandering to braiding within a reach (Figure 19.2). Knighton and Nansen (1993) attribute this tendency to an intermediate state whereby an imbalance exists among flow strength, bank erodibility, and relative sediment supply (Qs in - Qs out); but the direction of balance switches, causing the channel to be always near the threshold for planform change. The trigger for such switching is the high-magnitude, low-frequency flood event which can overcome low bank erodibility or low relative sediment supply, during a period of high flow strength. The channel change between 1867-1899 occurred during a period of increasing flood frequency (Rumsby & Macklin, 1994; Milne, 1982a) which is reflected in channel narrowing and a reduction in braiding index within the reach, possibly as a result of incision (Figure 19.3c). There were fewer floods between 1899 and 1925; the channel braiding index moderately increased, and the net floodplain budget rates remained positive, indicating contraction of the active floodplain swath (Figure 19.3a and 19.3b). Width changed little during this period, with the exception of the Phase 1 extraction reach. Although some five years before commercial extraction was permitted in this reach, the Northumberland River Board and County Council records document extraction by an aggregate business and local farmers during this period. The anomalous width increase, increased braiding index, and high rate of positive floodplain budget may reflect this initial activity.

Between 1925 and 1957, commercial gravel extraction had commenced in the Phase 1 reach and had extended into the lower half of the Phase 2 reach. There was an increased frequency of flooding, culminating in the 'Great Border Floods' of 1948 and 1949 mentioned above (Archer, 1992). Figure 19.2 and Figure 19.3a-19.3c reflect this activity. Floodplain budget rates are negative throughout the reach, indicating erosion of the channel margins and extension of the active floodplain width. Channel width also increases throughout the reach, but particularly in those reaches affected by gravel extraction where the magnitude of change almost reaches those reported for the 1948 flood. Braiding index decreases in the reaches upstream of the extraction sites, but remains high in the Phase 1 extraction site, again supporting the observation from contemporary post-flood reports. Gravel extraction was halted following these flood events, but had resumed by 1961 on Phases 2 - 4 so that by the 1966 survey, the Wooler Water had experienced extraction from the river bed from Wooler Bridge to the meander bend upstream of Haugh Head Ford (Figure 19.2). During this period, channel width decreased in all reaches except Phase 3. Braiding index increased in all extraction reaches but not in the reach unaffected by extraction. The magnitude of floodplain budget is high for the extraction reaches, probably as a result of the overall reduction in active floodplain swath. Extraction Phase 3 reach exhibits channel widening and maintains floodplain swath. Braiding index is



a. **Active floodplain budget rates, calculated by subtracting (Erosion T1 - T2) from (Deposition T1-T2) / Time step (yrs). Negative budgets indicate net rates of active floodplain expansion, positive values are net rates of active floodplain contraction.**

b. **Changes in channel width over the time period, indicating reductions following gravel extraction.**

c. **Changes in the values of braiding index for each reach, calculated after Coleman (1969).**

Figure 19.3. **Sediment budgets, active channel width and braiding index for the Wooler Water, 1860-1975.**

particularly high in his reach, which was the focus of active extraction during the period bounding the 1966 survey.

In terms of planform activity, the flood of August 1966 was not unusual for the Wooler Water. The effects of that flood are not revealed in the floodplain budget rates since they took place over a period of days rather than years and are therefore not directly comparable with the other data sets. Nevertheless, a net erosion budget is recorded for all except the Phase 1 and 2 reaches, indicating a general increase in active swath. During this flood, channel widths increased through all reaches with the exception of the Phase 2 extraction site. The braiding index decreased through the reach and increased only in the lower reaches associated with extraction Phases 1 and 2. Channel adjustment during the flood event is characterized by an increased sinuosity in reaches to Haugh Head Ford, channel widening through the Phase 2 extraction site, and a shift in channel location, similar to that described for the 1948 and 1949 floods on the Phase 1 extraction site. The magnitude of channel change is similar to those recorded for the longer time periods, suggesting either that it is large events that control channel change in the Wooler Water or that rates of channel change are much greater than those indicated by the time steps available for historic reconstruction using series cartographic evidence.

Following the flood of 1966, planform activity is characterized by a trajectory towards channel narrowing throughout those reaches affected by extraction, while the unaffected reach shows some channel widening. Rates of reduction in areas of active swath attain a maximum during the period 1966-1973, with evidence that this rate slowed between 1973 and 1975. The braiding index falls for all sites except the Phase 2 site, which became progressively dominated by braid bars to 1975. Contemporary field evidence shows this site to be a wide area of exposed gravels, through which the present channel meanders, with occasional bars suggesting a decrease in braiding index since 1975. Figure 19.2 illustrates the effect of channelization on channel planform in the Phase 4 reach. This was conducted as part of the extraction remedial works following a flood in 1971.

Channel planform in 1995 is much the same as that defined by the 1975 survey. Upstream of Haugh Head Ford, the channelization works artificially maintain planform, though the bank line is eroding. The present channel through Haugh Head Ford is single-threaded and gently sinuous, but increases in sinuosity as it enters the Phase 3 - 2 extraction reaches. A wide alluvial valley floor of disturbed gravels presents opportunities for avulsion, which are evident from the abandoned channels in these two reaches. In the downstream half of the Phase 3 reach, the channel becomes confined and almost canalized. Bank protection works downstream of Earle Mill artificially maintain the channel in a single-thread, gently sinuous planform through the Phase 2 and Phase 1 reaches.

19.6 VERTICAL INSTABILITY ON THE WOOLER WATER

The evidence for vertical instability on the Wooler Water is principally derived from re-surveys made by the relevant water authorities immediately before the flood of August 1966. However, the Holocene terrace system identified by Tipping (1994) indicates that vertical instability has been a feature of the Wooler Water over the past 7,000 years. Although no primary evidence for vertical instability is currently available for the period covered by the planform data, documented accounts do indicate that incision occurred during some of the larger floods of the late 19th century, which were responsible for removing fords at Coldgate Mill, and bridges throughout the reach (Archer 1992). Surveys of the terrace levels are currently underway to establish the vertical history of the channel over this time-period.

Figures 19.4 and 19.5 illustrate the longitudinal profile and cross section of the Wooler Water for the period immediately before the August 1966 flood, up to January 1995. This period is characterized by a reduction in channel width and active swath area during the run-down and cessation of extraction. Prior to 1966, the incision of the bed of the Wooler Water is documented, particularly in the area of Phase 1 and 2 extraction, which resulted in the exposure of a peat bed that temporarily acted as a grade control structure forming a waterfall 150 m downstream of Earle Mill (Figure 19.4). The impact of the 1966 flood was to destroy the peat bed waterfall (chunks of peat were removed from the channel in Wooler, 1,400 m downstream), along with the ford at Haugh Head. During the flood, local incision decreased in severity downstream from Haugh Head Ford, which clearly acted as a grade control despite destruction, reducing the upstream extension of incision into the Phase 4 extraction reach (Figure 19.4 and Table 19.3). Rates of incision were particularly severe in the reach immediately downstream of Haugh Head Ford since this had not been subject to extraction in order to protect the ford and footbridge.

Incision continued after the 1966 flood, and the ford and footbridge at Haugh Head were reconstructed. Extraction continued despite the channel instability until 1970, such that bed levels were further reduced by the time of the flood of March 1971. Figure 19.4 indicates that during the period between 1966 and the next survey in 1971 there were local bed level drops of up to 3.8 m, most of which could be attributable to direct removal of gravel from the bed of the Wooler Water. The 1971 flood, which by local accounts was not of the same magnitude as that of 1966, resulted in destruction of Haugh Head Ford, and the exposure of the footings of the footbridge (Figure 19.6). Incision extended upstream through the Phase 4 reach, since the contractors had failed to install the bed check weirs recommended by the local water authority following the flood of 1966. Erosion of the floodplain in the Phase 4 extraction reach cut off the old meander course shown in Figure 19.2. Figure 19.4 shows that aggradation occurred in the Phase 2 reach as a result of the 1971 flood, but that subsequently the channel cut through this, so that by 1972 the river bed lay below the 1971 level. Through the Haugh Head reach, reconstruction of the ford and the installation of six check weirs upstream of the ford resulted in aggradation to 1972; but Figure 19.5 reveals that the channel had incised below this level by 1975. Floods again in October 1981 dropped the bed level and threatened to undermine Haugh Head Ford. A bed check weir was installed 30 m downstream of the ford (some 16 years after it was recommended) and the intervening section filled with block stone.

The current position of the bed is the result of subsequent floods, notably that of 1992 which was, on many surrounding rivers, of greater magnitude than that of 1966. The bed level has again fallen by up to 3.4 m. However, Table 19.3 indicates that the trend since 1966 has been towards a reduction in the rate of incision, with these rates generally decreasing downstream from Haugh Head Ford. The latest survey indicates that the lower Phase 2 reach is currently aggrading, as sediments from the upstream incised reach are fed through the system.

The cross-section information in Figure 19.5 supports the phasing of incision of the channel since the period of extraction. Sections B and C are in

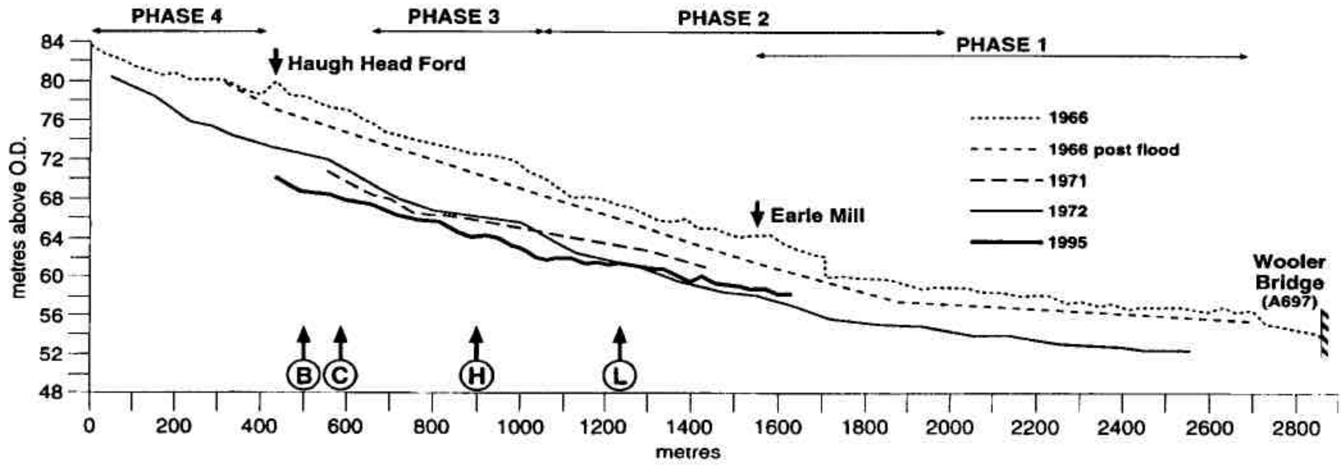


Figure 19.4. Longitudinal profiles for the Wooler Water 1996-1995, illustrating the progression of incision following gravel extraction.

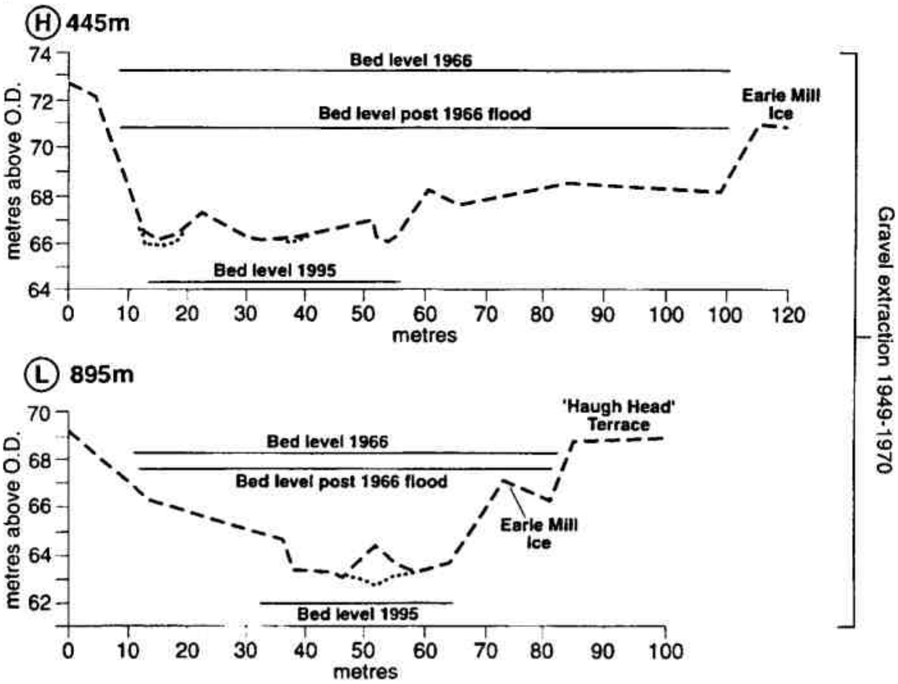


Figure 19.5. Cross sections for the Wooler Water, illustrating the effects of gravel extraction (Section H & L) and upstream incision through an unmined reach (Section B & C).

Table 19.3. Incision rates at sites downstream of Haugh Head Ford.

	Distance Downstream of Haugh Head Ford (m)				
Date	0	500	1000	1500	2000
1966 Flood	2.8	2.3	1.9	1.4	0.7
1966-1971	0.8	0.82	0.82	---	---
1971-1972	0.3	0.3	2	---	---
1972-1995	0.12	0.07	0.05	---	---
1966-1995	0.23	0.20	0.14	0.09	0.12

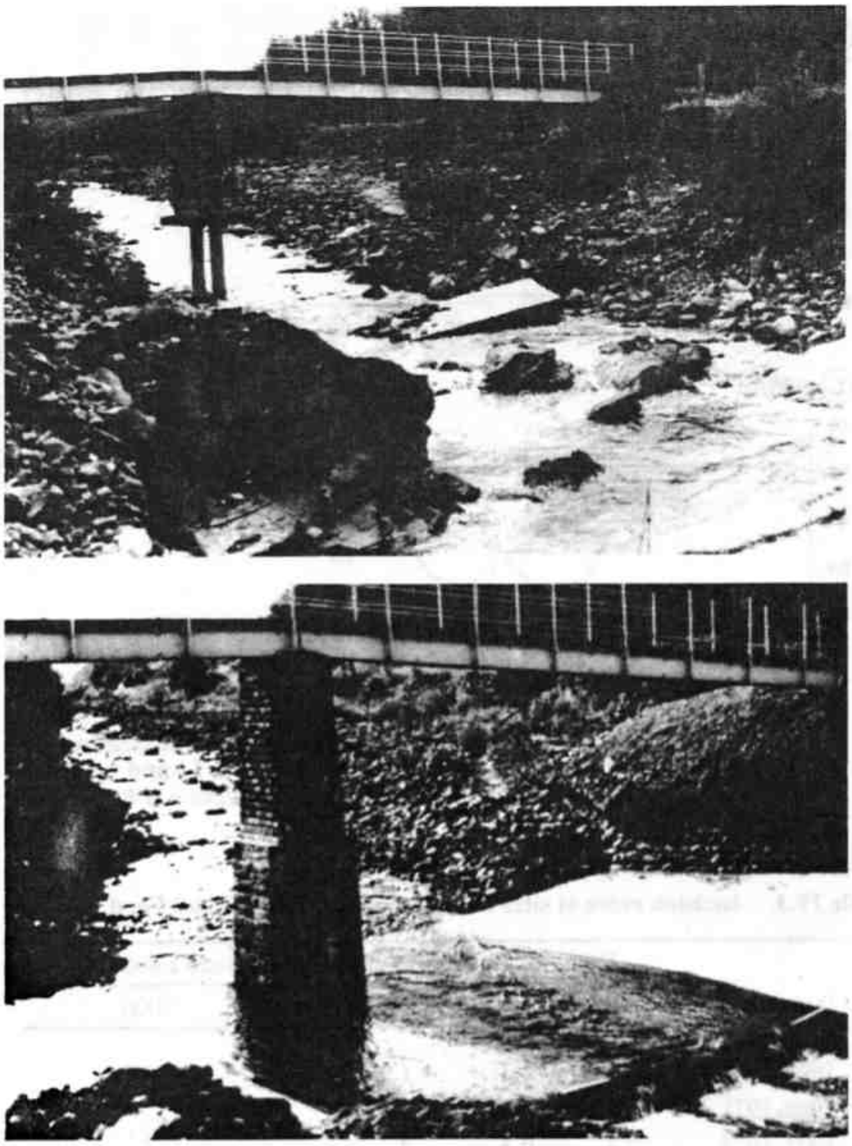


Figure 19.6. **Photograph looking upstream of Haugh Head Ford following the flood of March 1971 showing the exposure of the footbridge piers following incision (photo courtesy of Northumbria & Yorkshire region NRA).**

the reach where no extraction occurred and are characterized by confinement between steep banks of alluvial sands and gravels. This contrasts with sections H and L, which were in Phase 3 extraction where the mining has removed much of the adjacent gravels associated with the early Holocene alluviation episode described by Tipping (1994). The Earle Mill and terrace of Tipping

(1994) coincide with the post-1966 flood level, and as such appears to be in part, an artifact of gravel extraction (Section C in Figure 19.5). The two lower terrace units referred to by Tipping (1994) are certainly gravel extraction artifacts.

19.7 ANALYSIS OF GRAVEL-REMOVAL CHANGES

The removal of gravel from the bed of a river breaks the natural downstream continuum of sediment supply and therefore, from consideration of continuity, results in a downstream deficit over time. However, many of the gravel extraction sites from which reliable data are available were located in areas of net gravel storage where the supply of gravel was greater than the transport through the reach and where planform instability was a feature of the natural geomorphology. In these cases, removal of sediment at rates less than that at which it was supplied would have tended to preserve the site conditions and therefore maintain existing channel morphology. However, gravel extraction disrupts the armored elements of channel morphology, and presents a bed surface of over-loose and often finer grain sizes which facilitates rapid channel change and sediment throughput. In these circumstances, channel mobility is increased and rates of downcutting may also be exacerbated. Correspondingly, even in situations of extraction rates below those of supply, disturbance to the natural morphology could result in significant changes to the channel.

If gravel was extracted at a rate greater than the supply, net sediment deficiency would result and downcutting and apparent planform stability may be expected to occur. The removal of gravels at a rate below the natural rate of supply is difficult to achieve, given the considerable temporal instability in sediment transport. Nevertheless, it is interesting to compare the rates of extraction from sites in the northeast region with a simple empirical value of sediment yield. Table 19.4 records the main gravel extraction works together with the average volumes removed from each river on an annual basis. Figures for the annual sediment yield from each river at the point of extraction are

Table 19.4. Extraction yields in relation to sediment yield for sites in Northeast England for which reliable data exist.

River	Extraction Site	Catchment (km^2)	Sediment yield (m^3/yr.)*	Extraction yield (m^3/yr.)**	Ratio Extracted: Yield
Swale	Langton Bridge	630	1,667	458,715	275
Wear	Witton-le-Wear	455	1,143	73,045	64
Tyne	(All sites)	2,000	6,514	92,791	14
Coquet	Hepple	346	832	45,000	54
Wooler Water	Haugh Head	48	145	32,153	222
Breamish	Ingram	103	317	40,000	126

* calculated from Newson (1986; updated 1993)

** average annual extraction based on 5 year records (Northumberland County Council) given based on the catchment area equation of Newson, 1986 (modified 1993). Independent values of sediment yield for the Tyne are recorded by Hall (1964) for the period 1958-1960 at 7,668 m^3/yr. This suggests that the estimates based on catchment area are of similar magnitude, though probably an underestimate and certainly do not reflect any temporal changes in these values. The values in Table 19.4 suggest that the rates of extraction were in excess of the rate of sediment supply at each site, and that some form of vertical and lateral instability was to be expected. The records of the Northumberland River Board, and the Yorkshire Water Authority reveal evidence for channel instability at all sites recorded in Table 19.4, including the need for bed check weirs to control vertical instability of the river bed up to 2 km from the site of extraction at Witton-le-Wear. This site is still unstable; in the recent floods of February 1995, this site in particular experienced planform change some 20 years after cessation of gravel extraction.

The Wooler Water case study clearly shows a site that has been extracted beyond the rate of local supply. In terms of the continuum of channel pattern described by Knighton and Nansen (1993), the values for flow strength, bank erodibility and relative sediment supply may be expected to change. The changes indicated for the Wooler Water are given in Table 19.5.

Table 19.5. Changes of channel conditions for the Wooler Water due to gravel extraction.

Flow strength	Bank erodibility	Relative sediment supply	Channel pattern continuum
Initial condition and channel pattern:			
M/L	M/H	M/H	Wandering (the case for wandering gravel-bed rivers prior to extraction)
changing to:			
M/H	H	H	Braided (the case for the extraction site)
M/H	L	L	Straight/sinuous (the case downstream of the extraction site)
H	H	M/H	Braided (the case at the extraction site following incision upstream)

Where: H = high, M = moderate, L = low

The morphological impacts of extraction in phases upstream through a piedmont gravel-bed river are shown in schematic form in Figure 19.7. Following the Schumm *et al.* (1984) classification of incision processes, gravel extraction can be seen to reduce erosional resistance by disrupting armored bedforms and presenting a finer bed sediment for transport. This causes the channel to cross a threshold of stability which leads to planform changes characterized by increased channel and active swath widths and a higher braiding index. At the extraction site, increased relative sediment supply

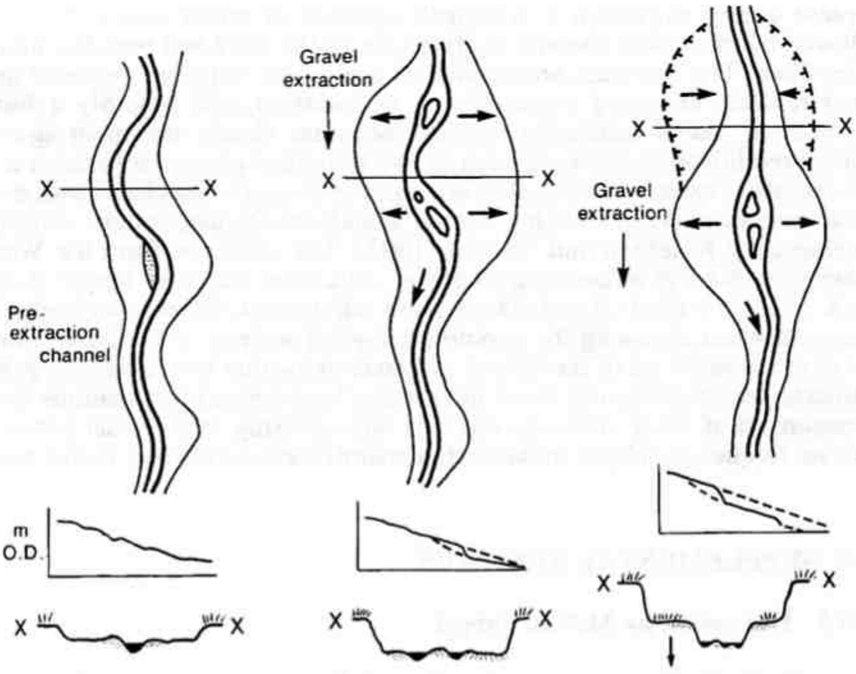


Figure 19.7. Schematic model of river channel response to phased gravel extraction based on the Wooler Water case study.

occurs due to the juxtaposition of upstream nick-point erosion and a reduction in reach capacity caused by over-widening. In the downstream reach, increased erosional forces following incision within the reach occurs through over-steepening of the channel slope and reduction in sediment supply, which leads to entrenchment and planform stability. Further upstream, extraction and/or incision continues to supply sediment to the downstream reaches through bank instability caused by the increasing bank heights (Sear *et al.* 1994). This may eventually lead to aggradation in the incised reach as sediment supply rates exceed the transport capacity of the lower reaches. Artificially maintaining a grade control, such as the Haugh Head Ford, can alter the rate of adjustment by maintaining steep slopes and reducing sediment supply to the downstream reaches. In areas where land uses allow, it may be more sustainable to permit natural adjustment to continue unchecked.

19.8 CONCLUSIONS

Gravel extraction, a global phenomenon, has been particularly prominent in the northeast region of England. There, most of the major gravel-bed rivers have been affected. Records from one site, the Wooler Water, indicate that up to 3.5 km of channel have experienced massive vertical instability and planform change over a period spanning 70 years. Incision and rates of planform change increase during extraction in a logical sequence of initial lateral instability, followed by increasing channel confinement as the river-bed trenches into the valley floor. The upstream progression of nick points supplies sediment to the lower reaches, resulting eventually in aggradation, and possibly a further sequence of lateral instability. Large floods are clearly the main agent of channel modification and have been shown to initiate phases of incision at the Wooler Water extraction sites. The sequence of changes associated with gravel extraction are predictable using simple models of channel pattern continuity developed by Knighton and Nansen (1993). The evidence from the Wooler Water suggests that adjustment to gravel extraction may take longer than 70 years, even in a channel capable of rapid adjustment. Correspondingly, it is important when assessing the geomorphological activity of piedmont gravel-bed rivers to be aware of the history of gravel extraction where records permit. Similarly, adjustments over these time scales have serious implications for the management of these channels and it is not suprising to find that extraction sites are frequently subject to the routine maintenance of the bed and/or banks.

19.9 SUPPLEMENTAL REMARKS

19.9.1 Discussion by M.N.R. Jaeggi

The experience described in the United Kingdom correspondsts which occurred in Switzerland around 1970. Where gravel extraction rates exceed supply rates, a net volume loss is obviously the consequence; and the adjustment can be slow or rapid. It was slow in the Alpine Rhine, where 20 million m^3 have been dredged between 1940 and 1970. The consequence was the distributed deposition of sediment over a long reach, such that local annual aggradation was small. Numerical simulation showed that this reach acts a gravel trap and that the gravel supply rate to the downstream reach forming the Swiss–Austrian border is extremely reduced compared to natural conditions; a situation having long-term aspects involving decades of change.

A fast reaction followed illegally excessive gravel extraction in the Ticino River (southern Switzerland). To protect an upstream bridge, rock had to be dumped into the river over several years. A head of 6 m ultimately developed in the channel and a block ramp had to be built, costing about US $ one million. Block ramps are to the sometimes dramatic effecstable only if the banks are protected by the same blocks as used for the ramp, at least in the lower part of the structure.

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