Sediment Dynamics and the Hydromorphology of Fluvial Systems (Proceedings of a symposium held in Dundee, UK, July 2006). IAHS Publ. 306, 2006.

Sediment yields in the Exe Basin: a longer-term perspective

ANNA HARLOW, BRUCE WEBB & DES WALLING

School of Geography, Archaeology and Earth Resources, Department of Geography, Amory Building, Rennes Drive, Exeter EX4 4RJ, UK

a.harlow@exeter.ac.uk

Abstract In the UK, fine sediment is viewed increasingly as a diffuse pollutant due to its role as a vector for the transport of potential contaminants, and in causing siltation, which may have adverse effects on river and estuarine habitats. There is a need, therefore, for river managers to have reliable information on sediment budgets in order to plan measures that will achieve "good" status under the EU Water Framework Directive. As part of a wider sediment-budget investigation in the EU-funded Cycleau Project, detailed records of fine sediment yield over the 10-year period from 1994–2003 have been analysed for the Exe Basin (1500 km^2), a principal river system of southwest England. The longer-term average yields in the three major tributaries of the Exe Basin are discussed and results of monitoring of sediment loads at a site near the tidal limit over a one-year period confirm the importance of the River Exe in contributing sediment to the Estuary.

Key words diffuse pollution; Exe Basin and estuary; longer-term behaviour; suspended sediment yields

INTRODUCTION

River systems provide a key pathway along which fine sediment (silt and clay particles of <63 µm in diameter) is transferred from the terrestrial to the estuarine environment. Suspended sediment can have a detrimental effect on the aquatic environment in a number of ways through both its physical presence in the water body and as a vector for sediment-associated transport of nutrients and contaminants (Waters, 1995). Effects range from the eutrophication by nutrients (Duda, 1993), reduction of DO availability to incubating salmon embryos (Greig *et al*., 2005) to the siltation of shipping channels in estuaries and coastal waters. For the UK, it is known that annual suspended yields generally range from <1 t km^{-2} year^{-1} to 500 t km^{-2} year^{-1}, with a typical value of 50 t km^{-2} year^{-1} (Walling & Webb, 1987). However, there are relatively few detailed and longer-term records of sediment loads on which river managers could base an assessment.

The present study is part of a wider sediment-budget investigation which is collating information for the Exe Basin in relation to its estuary in the context of the EU-funded Cycleau Project that is concerned with interactions between the land and the coastal zone in northwest Europe. The Exe Basin is a principal river system of southwest England and has been the subject of intensive study of many aspects of the dynamics, properties, sources, transport and sinks of suspended sediment since the early 1970s (Webb *et al*., 1995; Collins *et al*., 1998; Simm & Walling, 1998). The existing records of suspended sediment load for the Exe Basin are among some of the most detailed available for the UK and provide a longer-term perspective on fine sediment transport than is available for most rivers in the country (Webb & Walling 1982, 1984). In this paper, the analysis

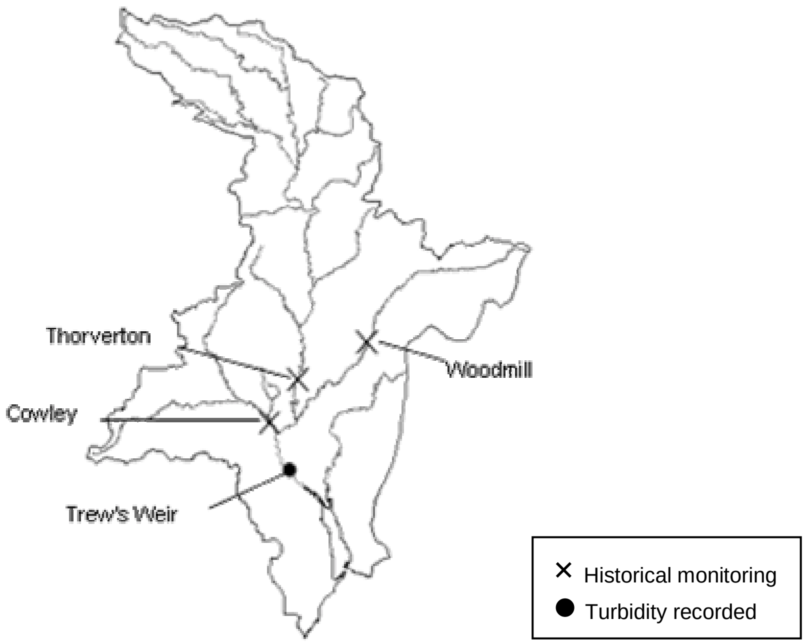

Fig. 1 The study catchment

of existing data is supplemented by the results of field monitoring at a hitherto unstudied site near to the tidal limit of the river system, in order to improve assessment of the delivery of sediment to the estuarine zone.

THE STUDY BASIN

The Exe Basin (Fig. 1), which drains an area of approximately 1500 km^2, has three major geological sub-units comprising Devonian slates and grits in the north, Carboniferous sandstone and shale sequences in the west and central parts, and a variety of Permian and younger sediments in the south and east. This variation in geology is reflected by the topography and hydrometerological conditions within the basin. Mean annual precipitation is at a maximum of 1800 mm on the highest ground of the Exmoor uplands in the north, but decreases to 800 mm in the lowlands around the head of the Exe Estuary in the south. Land use in the catchment varies from unenclosed moorland to arable cultivation, with the majority of the area under permanent pasture. The River Exe flows into the Exe estuary, which is environmentally important and classified as an SSSI, RAMSAR and Special Protection Area site. It is important to the local community as both a shellfish production area and a tourist attraction and it is also used for recreational purposes.

EXISTING RECORDS AND FIELD MONITORING

Suspended sediment loads for a 10-year period (1994–2003) were calculated from existing data for the River Exe at Thorverton, the River Creedy at Cowley and the

River Culm at Woodmill, which are the three major tributaries of the Exe Basin (Fig. 1). Discharge data, at 15-min intervals, were available from Environment Agency gauging stations, and for suspended sediment concentrations recorded by the University of Exeter using a combination of single gap and infra-red turbidity monitors calibrated against spot-measurements of mean sediment concentration in the cross-section. Together, these provided the basis for computing hourly, daily, monthly and annual loads at the three catchments.

For the purposes of the present study, a monitoring site was installed at Trew's Weir close to the tidal limit of the River Exe (Fig. 1). Over a 12-month period between August 2004 and July 2005, suspended sediment concentration was monitored every 15 min using a nephelometric turbidity probe calibrated against suspended sediment concentrations sampled from the cross-section. Equivalent flow data were available from an Environment Agency gauging station at the same location. Again sediment loads were obtained by combining the detailed sediment concentration and flow records.

RESULTS

Study-period averages

Table 1 summarizes the study-period averages for both flow and sediment load for the main tributaries and shows largest values, both in absolute terms and on a per unit area basis, for the main River Exe. On average, the Exe accounts for approx. 70% of the total sediment load and runoff delivered by the three tributaries, although it makes up just over 50% of the total catchment area. The relatively high sediment loads and yields of the River Exe above Thorverton reflect the influence of its tributaries and especially the River Dart which has a particularly steep topography and the River Lowman which drains an area of largely arable cultivation on relatively erodible Permian sedimentary rocks. The Rivers Creedy and Culm, which have similar sized catchments, both have much lower average flows than the Exe, reflecting their smaller catchment areas. However, reasonably high sediment yields in these catchments may also be related to the occurrence of less resistant post-Carboniferous rocks and more intensive agricultural practices in these catchments. The somewhat higher average sediment loads and yields in the River Creedy compared to the River Culm is most likely a consequence of the steeper nature of the former catchment.

Table 1 Average flow and suspended sediment yield in the Rivers Creedy, Exe and Culm (1994–2003).

	Exe (Thorverton)	Culm (Woodmill)	Creedy (Cowley)
% Total area	55.8	20.8	24.0
Average flow ($m^3 s^{-1}$)	17.8	4.3	3.7
Average specific flow ($L\ s^{-1}\ km^{-2}\ year^{-1}$)	29.6	18.8	14.0
% Flow contribution	69.2	16.5	14.3
Total sediment load (t)	272837	53905	85057
Specific sediment yield ($t\ km^{-2}\ year^{-1}$)	45.4	23.9	32.5
% Sediment contribution	67.6	13.3	19.1

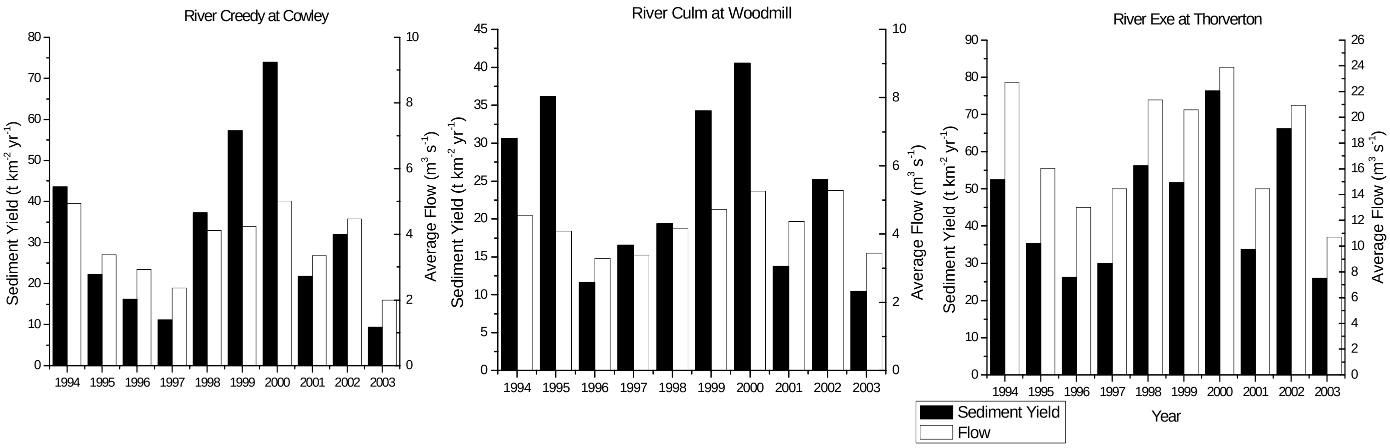

Fig. 2 Annual sediment yield and annual average flow in the major tributaries of the study catchment.

Annual yields

Annual sediment yield and flow values were examined for trends over the 10-year study period (Fig. 2). At each site, sediment yields and flow follow a broad pattern with an increase in flow leading to an increase in sediment yield. In 1999 and 2000, both the River Creedy and Culm have somewhat higher sediment yields but do not display an associated increase in flow. This is likely to reflect the particular pattern of flood events in these years as compared to other years. In 1999 both the Culm and Creedy experienced significant flow events that were distributed throughout the year, rather than predominantly in winter months with summer months contributing significantly higher sediment yields than other years. In 2000, the majority of the large storms occurred from October to December contributing 88% and 84% of the total sediment load for that year at Cowley and Woodmill respectively, with the remainder of the year having relatively few high magnitude events. Calculation of the coefficient of variation values suggests that annual flows are more variable in the Creedy (77.6%) than in the Exe (63.7%) and in turn the Culm (50.6%), which reflects a somewhat greater groundwater influence in the latter tributary. The annual variability of suspended sediment yields is higher than that of flows as indicated by coefficient of variation values of 116.3, 96.4 and 88.8% associated with the Creedy, Culm and Exe, respectively. There is little evidence of systematic increases or decreases in flow or sediment yield over the study period in the Exe tributaries, and no clear effect on suspended sediment loads of the foot and mouth cattle disease outbreak in 2001, which resulted in reduced livestock numbers.

Plotting of annual sediment load against annual mean flow for the individual sites (Fig. 3) reveals a general relationship as expected, although there is some scatter indicating the effects of storm type and antecedent conditions, as well as flow volume, on sediment transport. The slope of the fitted relationships suggests suspended sediment load is more sensitive to increasing annual flow in the River Exe than in the Rivers Creedy and Culm.

The relative contribution of each tributary to the combined annual sediment loads of these major tributaries over the study period is depicted in Fig. 4. The Exe dominates the combined total of suspended sediment yield in all years. However, the contribution of this tributary is variable and accounted for less than 60% of the total load in 1995 and 1999. The River Culm generally contributes the smallest proportion of the total annual sediment load but it exceeded that of the River Creedy in 1997 and especially in 1995 (Fig. 4), when some high magnitude storms with relatively high sediment concentrations in excess of 500 mg L^{-1} occurred in this catchment. A similar explanation accounts for the greater contribution of the River Creedy to combined sediment loads in 1999 and 2000 as these years saw a number of large events with relatively high sediment concentrations (>800 mg L^{-1}).

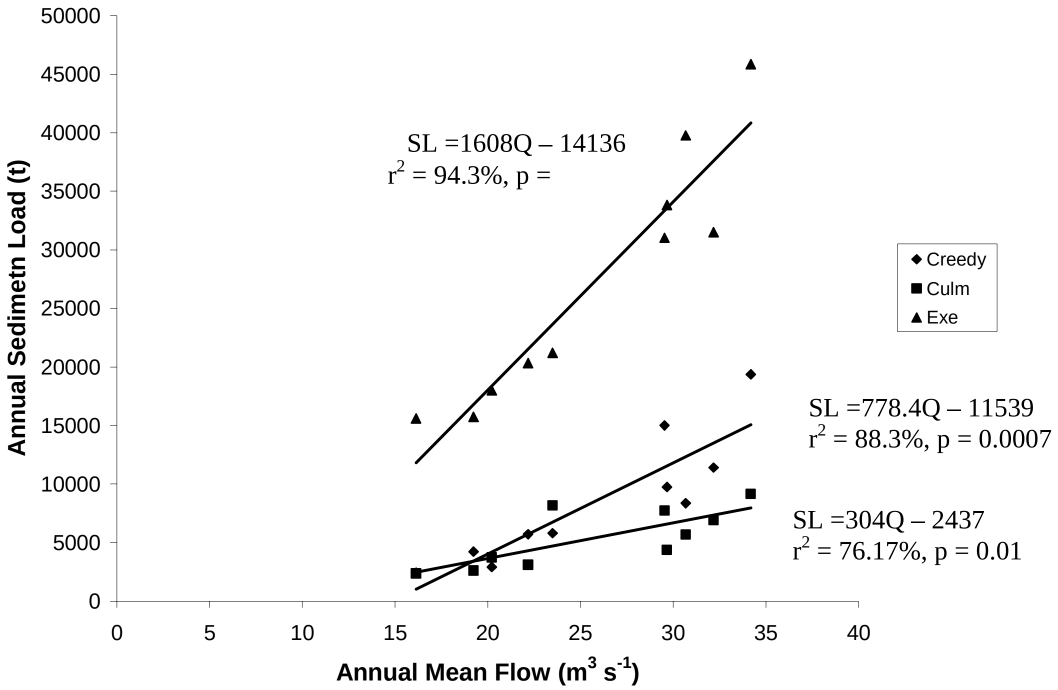

Fig. 3 Relationship between annual sediment yield (SL) and annual mean flow (Q) in the main tributaries of the study catchment and associated r^2 values and regression equations.

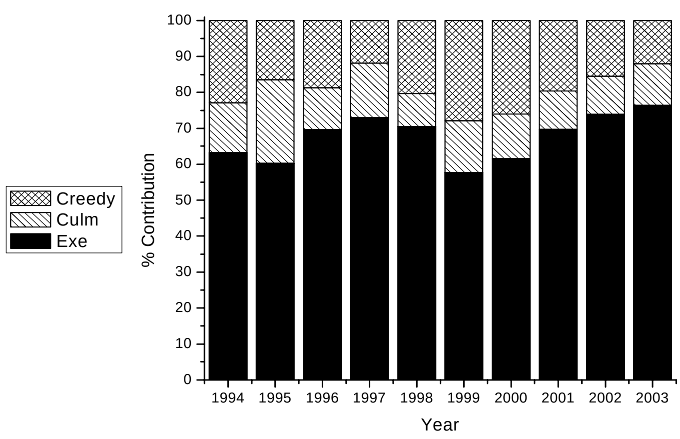

Fig. 4 The relative contribution of each tributary to the sediment loads of the major tributaries in the Exe Basin over the study period.

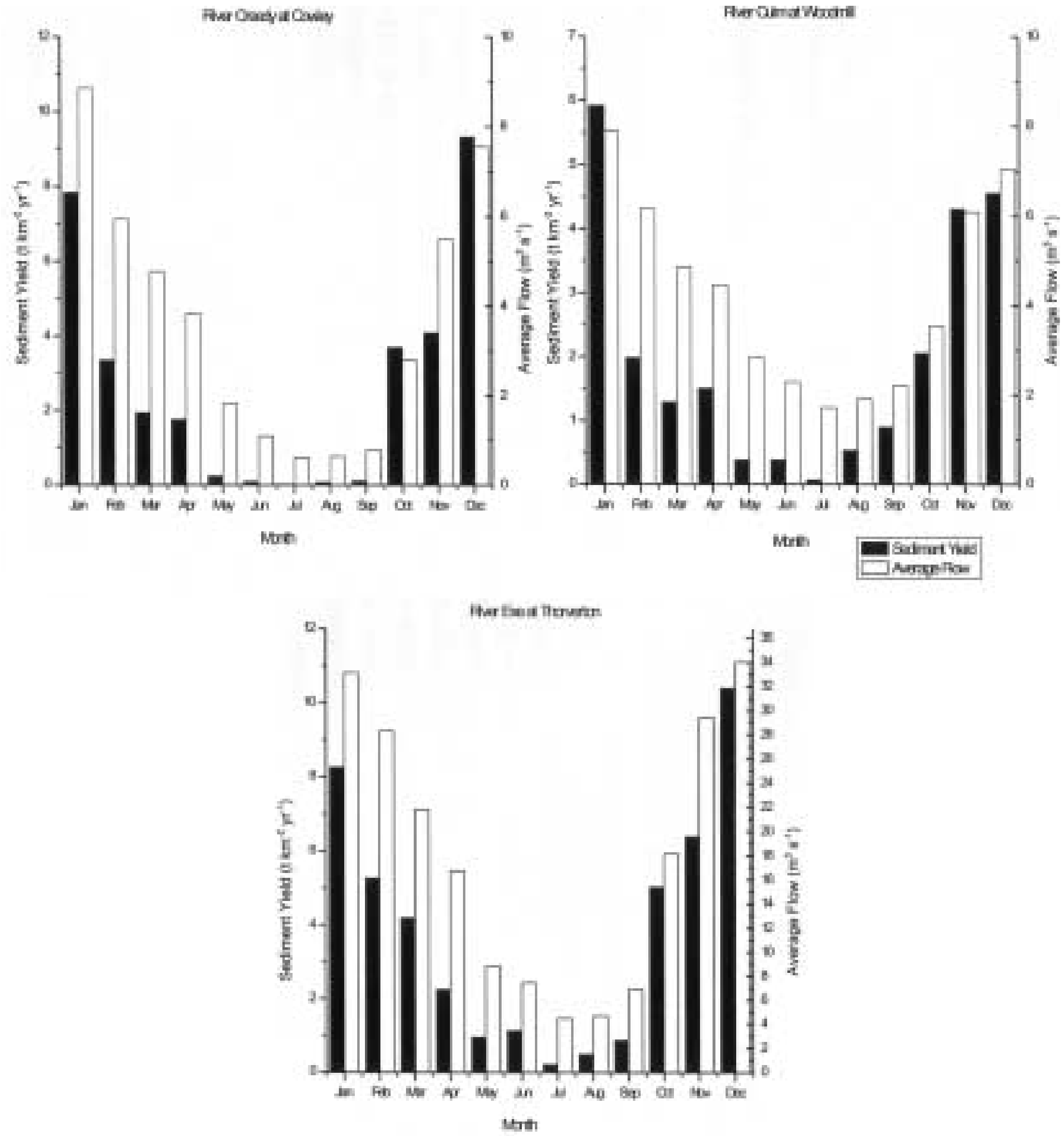

Fig. 5 Seasonal patterns in flow and sediment load in the main tributaries of the study area.

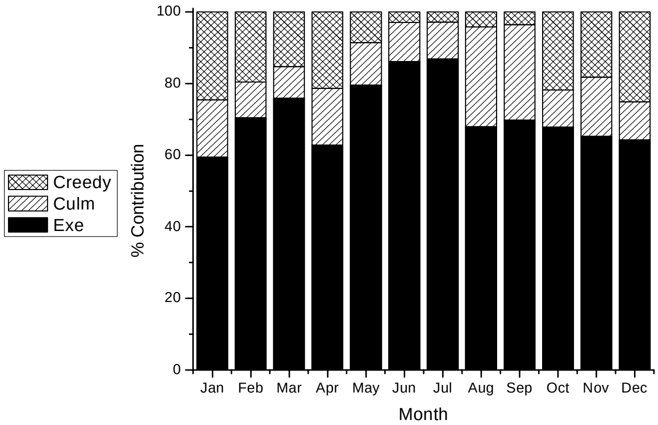

Fig. 6 The relative contribution of each tributary to the combined total average sediment load for each month of the year.

Seasonal variations

The average seasonal variation in flows and sediment loads for the major Exe tributaries is depicted in Fig. 5, which reveals the expected concentration of transport in the winter months (October–March).

In the months from October to December loads tend to be higher than those for January to March for equivalent volumes of flow suggesting some general exhaustion of sediment sources over the winter period.

The relative contribution of each tributary to the combined total sediment load for each month of the year is depicted in Fig. 6. The Exe is dominant throughout the year and especially in the mid-summer period when it accounted for more than 80% of the combined total.

Downstream loads

The sediment load at Trew's Weir in the period from August 2004 to July 2005 was 21 891 t. The combined load from the three main upstream tributaries monitored at Cowley, Woodmill and Thorverton over the same period was calculated as 21 125 t, which represents more than 96% of the sediment load at the downstream site. For this 12-month period, the fluxes of suspended sediment monitored at Thorverton, Cowley and Woodmill were 17 492, 2405, and 1227 t, respectively, which represented 80, 11 and 6% of the load recorded at Trew's Weir. These data confirm the main Exe tributary to be the major contributor of sediment to the Estuary. The fact that the sediment load at Trew's weir is in excess of the combined total in the three major upstream tributaries suggests there are not major sediment sinks downstream of the monitoring sites at Thorverton, Cowley and Woodmill. Whilst the use of continuous data monitoring increases the accuracy of flow and sediment load estimates, measurement and calibration errors still inevitably introduce some uncertainties into calculated fluxes. Nevertheless, the additional 766 t recorded at Trew's Weir is not inconsistent with material being transported from the many smaller tributaries that are present in the 102 km^2 of unmonitored area between Trew's Weir and the upstream stations. Figure 7 compares for individual months between August 2004 and July 2005 the sediment load measured at Trew's Weir and in the upstream tributaries. Both graphs show an expected seasonal cycle of increased sediment load in the winter months. The contribution of sediment from the Exe is the dominant component of the load at Trew's Weir in all months of the year, partly reflecting the larger drainage area and greater volume of flow generated in this tributary. The suspended sediment transported by the rivers Creedy and Culm constitutes a more significant proportion of the load at Trew's Weir in October, December and January when flow volumes yielded by these catchments were greater. In December 2004, the total sediment load of the three upstream tributaries exceeded that at Trew's Weir suggesting that there was some storage of sediment either in the channel or on the flood plain downstream of Thorverton, Cowley and Woodmill. In the other months of the monitoring period, the downstream load exceeded that of the main tributaries suggesting such storage did not occur. While highest flows were recorded in January 2005, sediment loads were

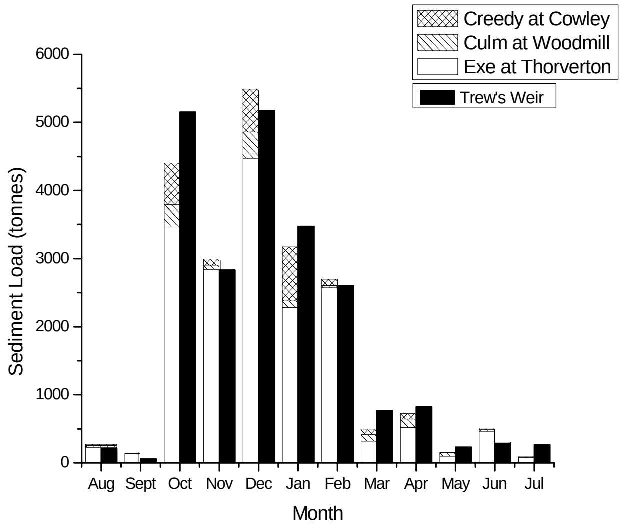

Fig. 7 Sediment load monitored at Trew's Weir and at the main upstream tributaries in the period from August 2004 to July 2005.

lower than in October and December, 2004, which indicates that there may be an element of sediment exhaustion over the winter period as suggested by the longer-term data for the upstream tributaries.

CONCLUSIONS

The longer-term data from the Exe Basin do not suggest any systematic trends in suspended sediment transport over recent years and do not evidence a clear impact on sediment loads of the foot and mouth outbreak that provided a major recent perturbation in agricultural activity in the study catchment. There is, however, some evidence of a sediment exhaustion effect operating in this catchment such that autumn and early winter transport is greater than that in late winter and early spring at the same level of flow. Of the major tributaries, the main Exe, draining the middle and upper parts of the basin, makes a dominant, although not always constant, contribution to the sediment supplied to the estuary and is more sensitive to varying flows than the Creedy and Culm which drain the lowlands of the south.

A longer-term perspective on sediment delivery to the estuary, together with information on the sources of fine sediment in this catchment, will assist river managers in meeting the Water Framework Directive criteria. In attempting to assess how sediment delivery to the estuary might alter in the future under different scenarios of climate and land-use change, attention should be focused on the upper and middle portion of the Exe Basin as main contributor to the sediment load.

REFERENCES

Collins, A. L., Walling, D. E. & Leeks, G. J. L. (1998) Fingerprinting the origin of fluvial suspended sediment in larger river basins: combining assessment of spatial provenance and source type. *Geogr. Ann.* **79A**(4), 239–254.

Duda, A. M. (1993) Addressing nonpoint sources of water-pollution must become an international priority. *Water Sci. Technol.* **28**, 1–11.

Greig, S. M., Sear, D. A. C & Carling, P. A. (2005) The impact of fine sediment accumulation on the survival of incubating salmon progeny: implications for sediment management. *Sci. Tot. Environ.* **344**, 241–258.

Simm, D. J. & Walling, D. E. (1998) Lateral variability of overbank sedimentation on a Devon flood plain. *Hydrol. Sci.* **43**(5), 715–732.

Walling, D. E. & Woodward, J. C. (1995) Tracing sources of suspended sediment in river basins: a case study of the River Culm, Devon, UK. *Mar. Freshwater Res.* **46**, 327–336.

Waters, T. F. (1995) *Sediment in Streams—Sources, Biological Effects and Control*. Americal Fisheries Society Monograph, Bethesda, Maryland, USA.

Walling, D. E. & Webb, B. W. (1987) Suspended load in gravel bed rivers: UK experience. In: *Problems of Sediment Transport in Gravel Bed Rivers* (ed. by C. Thorne, J. Bathurst & R. Hey), 691–732. Wiley, Chichester, UK.

Webb, B. W., Foster, I. D. L. & Gurnell, A. M. (1995) Hydrology, water quality and sediment behaviour. In: *Sediment and Water Quality in River Catchments* (ed. by I. Foster, A. Gurnell & B. Webb), 1–17. Wiley, Chichester, UK.

Webb, B. W. & Walling, D. E. (1982) The magnitude and frequency characteristics of fluvial transport in a Devon drainage basin and some geomorphological implications. *Catena* **9**, 9–23.

Webb, B. W. & Walling, D. E. (1984) Magnitude and frequency characteristics of suspended sediment transport in Devon rivers. In: *Catchment Experiments in Fluvial Geomorphology* (ed. by T. Burt & D. Walling), 399–415. Geo-books, Norwich, UK.