Suspended sediment behaviour and sources in the catchment of the Helford River, Cornwall, UK

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Fine sediment (particles <63 µm) carried by the Helford River was investigated in 16 sub-catchments above the tidal limit for the period 1 June 2005 to 31 May 2006. Equipment for continuous monitoring of turbidity and river stage (height) was installed in the six largest tributaries and revealed the importance of storm events and the dominance of winter months for sediment movement, but also some complexity with intra- and inter-storm exhaustion of fine sediment supply. It was estimated that >2000 tonnes of suspended sediment were delivered to the tidal limit in the study year. Modified Phillips traps were also deployed in all 16 sub-catchments to collect samples for a 'fingerprinting' (tracing) study of sediment sources involving comparison of river-borne suspended sediment properties with those of potential source materials sampled from different geological and land-use units and channel banks at 569 locations in the catchment area. This showed that the various geological units contributed suspended sediment largely in proportion to their area of outcrop, but grassland and cultivated fields were of equal importance as major sediment sources, despite the considerably smaller area occupied by the latter. Channel banks were also a significant contributor of suspended sediment, but spatial and temporal variability in the contribution of land-use sources was also evident.

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Introduction

The influence of historical mining on the transfer of sediment to Cornish estuaries has attracted considerable interest involving geochemical and mineralogical investigations of the sediment deposited in the Helford (Pirrie *et al.*, 2002a), Fal (Pirrie *et al.*, 1997, 2003; Hughes, 1999) and Fowey estuaries (Pirrie *et al.*, 2002b) on the south coast, and in the Hayle (Rollinson *et al.*, 2007) and Gannel and Camel estuaries (Pirrie *et al.*, 2000) on the north coast. Less attention perhaps has been paid to the nature and source of fine sediment being transported presently in Cornish river systems, although Richards (1979) reported very high suspended sediment concentrations (>50,000 mg l^{-1}) in water courses draining areas of china clay working in the St Austell district, and Yim (1981) investigated suspended sediment influenced by mine tailings in the Red River of West Cornwall. As part of a study of sediment-associated pesticide transport in the Mount's Bay catchment, it was noted that suspended sediment concentration varied between 2 and 7 mg l^{-1} in baseflow conditions, but rose to between 12 and 1,720 mg l^{-1} in winter spates (Harrod & Theurer, 2002). A reconnaissance survey of the source of interstitial fine sediment recovered from salmonid spawning gravels in England and Wales (Walling *et al.*, 2003) indicated that a high proportion of this material in Cornish rivers originated from channel bank and subsurface sources, such as drains, rather than from surface erosion of fields. In the Camel, Fal, Fowey and Lynher, between 97 and 88% of the fine interstitial sediment in river gravels was attributed to bank erosion or subsurface sources, and this reflected widespread poaching (damage to the sward by animal hooves) and degradation of channel margins and banks by livestock, the frequent existence of subsurface drains that discharge into permanent watercourses, and ditching activities in moorland areas drained by these rivers (Walling *et al.*, 2003).

The present study focussed on improving the understanding of the behaviour, transport and sources of suspended sediment in a Cornish river system and was undertaken as part of the Cycleau Project, which involved co-operation between partners in South-West England, Brittany and Ireland to find innovative ways of managing and improving the water environment, to share knowledge and experience of water management and to involve local communities in the management of local rivers. The study catchment was the Helford River (Figure 1) which drains parts of the Carnmenellis, Lizard and Cornish Killas character areas defined for Cornwall by Natural England (*http://www.naturalengland.org.uk/ourwork/landscape/englands/character/areas/default.aspx*). The total drainage area to the Helford Estuary is *c.* 115 km^2, and elevation reaches a maximum of *c.* 200 m on the northern watershed. Mean annual precipitation varies from 1,141 to 1,380 mm, with the northern side of the catchment being wetter than the southern (Met Office, 2000), and mean annual runoff is estimated to vary from 400 to 800 mm. The main land use in the study area is

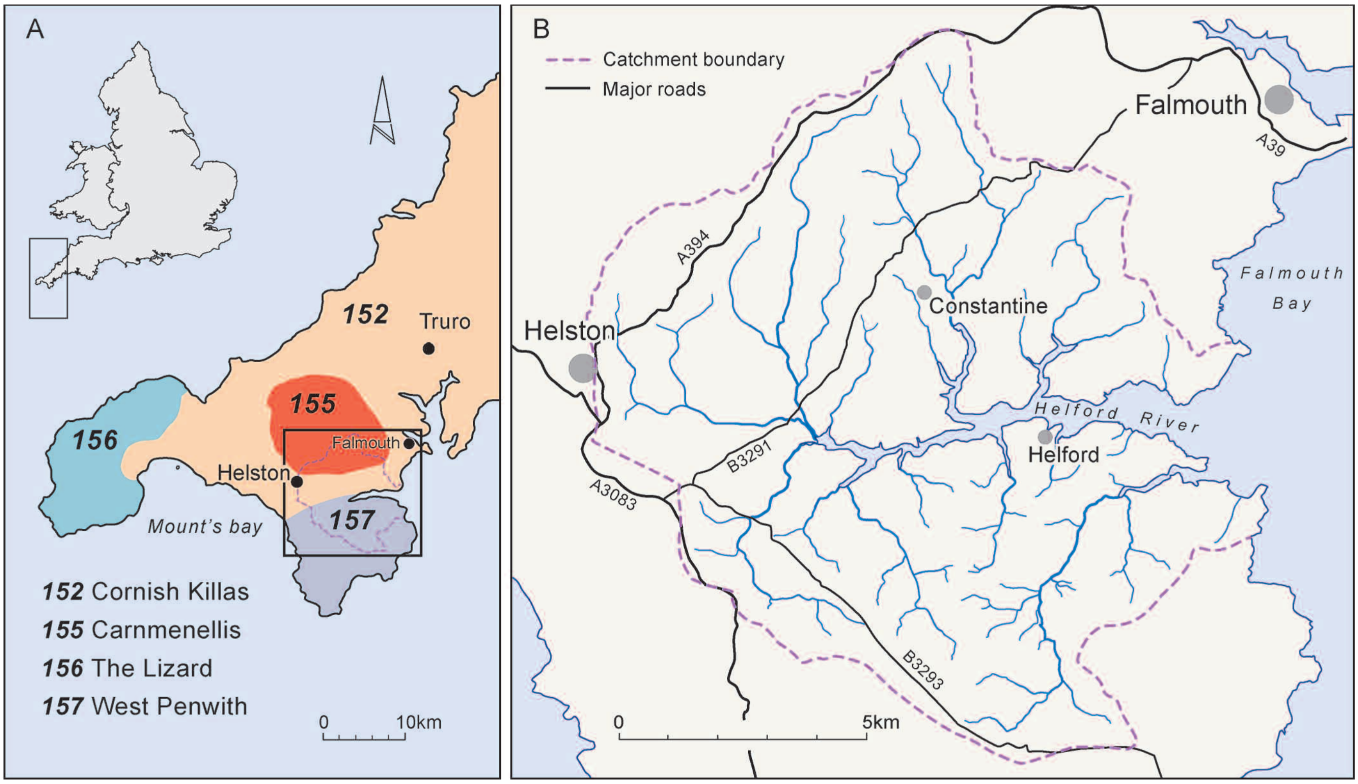

Figure 1. *The Helford River, Cornwall, UK. (**a**) Location in relation to Character Areas (from Natural England http://www.naturalengland.org.uk/ourwork/landscape/englands/character/areas/default.aspx accessed 22nd February 2012). (**b**) Catchment area.*

agriculture. Data from the 2004 June Census (Defra, 2004) revealed that permanent pasture for dairy and beef cattle is the dominant land use comprising >44 and >48% of the area on the northern and southern sides of the catchment, respectively. Crops, which include daffodils, potatoes and winter cauliflower and cabbage, plus fallow land account for 28% of the northern part of the Helford and >17% of the southern part. Temporary grassland and rough grazing occupy >18% and >29% of the northern and southern sides of the study area, respectively, while the area under woodland is restricted to <4% in the north and <3% in the south.

The Helford catchment is varied geologically (Figure 2). The north of the catchment is underlain by the Carnmenellis Granite and the south by rocks of the Lizard Complex, while the central area drains various Devonian strata caught up in a number of Variscan thrust nappes (Leveridge *et al.*, 1990; Pirrie *et al.* 2002a). The geological units considered in the present study were derived from the information portrayed on the 1:50,000 drift editions of sheets 352 and 359 produced by the British Geological Survey and the names shown on this source are used throughout this paper. The equivalent current nomenclature from Edina Geology Digimap is shown in Table 3.

Methods

Sixteen sites, located on the main tributaries of the catchment as close as practically possible to the tidal limit, were selected for investigation (Table 1). The upstream sub-catchment areas (Figure 3) were determined using a Digital Elevation Model constructed within ESRI ArcGIS 8.3, and sum to a total area of 92.6 km^2 above the tidal limit.

River monitoring

Continuous monitoring of suspended sediment concentration and discharge was undertaken for the six largest tributaries which comprise three sites on the northern side of the catchment (Gweek North, Gweek West, Polwheveral) and

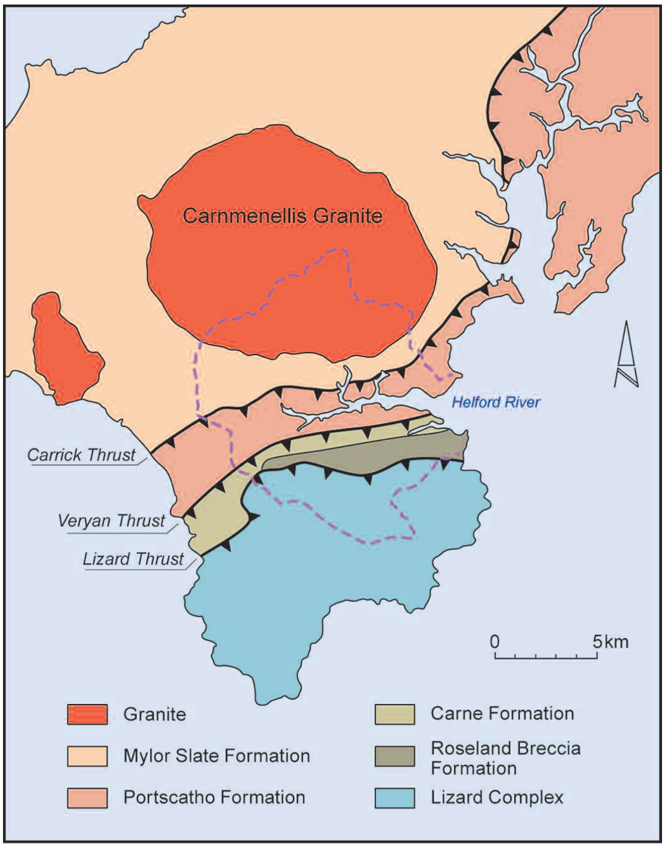

Figure 2. *Geological map of the region around the Helford River. From Pirrie et al. (2002a).*

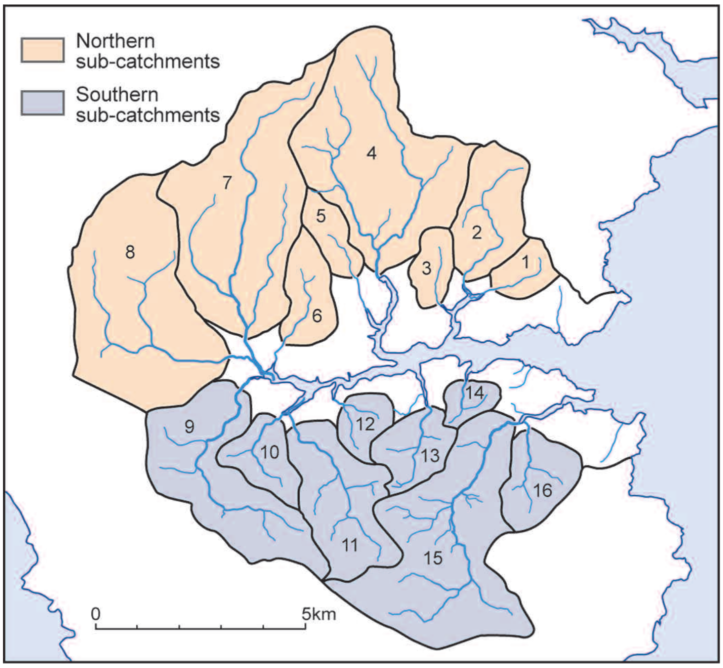

Figure 3. *Location of the study sub-catchments. Numbers refer to Table 1.*

Sub-Catchment	**Sub-Catchment Number**	**Area km^2 (above the tidal limit)**
Gweek North	7	14.48
Gweek West	8	13.99
Polwheveral	4	13.61
Gillan - Manaccan	15	13.33
Ponsontuel	9	8.56
Trelowarren	11	6.19
Trenarth	2	4.02
Gillan - Carne	16	3.12
Bonallack	6	2.92
Frenchmans	13	2.66
Mawgan	10	2.41
Constantine	5	1.65
Bonnal	12	1.56
Penpol	1	1.53
Porth Navas	3	1.52
Helford	14	1.01

Table 1. *Details of the study sub-catchments.*

three on the southern side (Gillan-Manaccan, Ponsontuel, Trelowarren) and together account for *c.* 75% of the study area. Suspended sediment concentration was determined through measurements of turbidity made with McVan Instruments Analite NEP9504 self-cleaning turbidity probes. Self-cleaning of the probe lens was effected by a wiper blade, which operated at a 12-minute interval and prevented the build up of an algal film that may distort turbidity readings if not removed. The accuracy of the turbidity probes was checked routinely with reference to a 1,000 ppm formazin standard solution. Discharge was monitored via measurements of river stage (height) which was determined by a Campbell Scientific PDCR1830 pressure sensor mounted together with the turbidity probe in the river channel at each site. Turbidity and river stage data were measured every 60 seconds and the lowest value in each 15-minute period was recorded using a Campbell Scientific CR10X data logger housed in a robust secure weatherproof casing located on the river bank. The monitoring equipment was powered by 12 V 7.2 AH rechargeable sealed lead acid batteries which were sufficient to run the systems for a period of approximately three weeks between field visits undertaken for maintenance and data downloading.

Conversion of turbidity measurements into suspended sediment concentration, and river stage into discharge data, was based on a programme of field calibration. Suspended sediment samples (*c.* 500 ml) were collected over a range of flow conditions at each site, and concentrations for comparison with corresponding turbidity measurements were established by filtration, drying and weighing. Calibration of turbidity probes against the highest suspended sediment concentrations, which were difficult to sample in the field because of their relatively rare occurrence, was undertaken using a 1,000 mg l^{-1} sample artificially made up from a range of soil materials collected from the catchment that were dried and sieved to <63 μm. In order to convert the river height (pressure) data to flow values, stage/discharge rating relationships were constructed for each site by a programme of river gauging over a range flow conditions using a Valeport 'Braystoke' BFM002 current meter.

The equipment for monitoring the six largest tributaries of the Helford River was installed in the spring of 2005 and removed in the autumn of 2006. Data on suspended sediment concentration and discharge were analysed for a 12-month period extending from 1 June 2005 until 31 May 2006.

Sediment source fingerprinting

The sources potentially supplying suspended sediment to the Helford tributaries were investigated using a fingerprinting (tracing) approach (Collins and Walling, 2004; Walling, 2005) which is based on a comparison of the properties of the suspended sediment carried by the river with those of potential source materials in the upstream sub-catchment area, and comprised two stages. In the first, the ability of a combination of properties in a composite fingerprint (Collins and Walling, 2002) to discriminate between source materials classified according to geological units and to surface material under different land uses and channel banks was tested statistically. This involved firstly the use of the Kruskal-Wallis H test to establish the ability of individual properties to discriminate between different source material groupings, and secondly the application of multivariate discriminant function analysis, using the minimisation of Wilk's lambda in a stepwise selection algorithm, to select the optimum composite fingerprint from those properties that were identified as statistically significant discriminators in the first test. In the second stage of the fingerprinting approach, the relative contribution of the various potential sediment source materials to the suspended sediment carried in the river was established by applying a mixing model using a linear optimisation algorithm. The proportions (*P*) contributed by the m individual sources (*s*) were established by minimising the sum of the squares of the residuals (R_{es}) for the n tracer (fingerprinting) properties involved, where:

$$R_{es} = \sum_{i=1}^{n}\left(\frac{C_{ssi} - (\sum_{s=1}^{m} C_{si}P_s)}{C_{ssi}}\right)^2$$

and C_{ssi} is the concentration of tracer property *i* in the suspended sediment, C_{si} is the mean concentration of tracer property *i* in the source group material (*s*) and P_s is the relative contribution of the source group material (*s*) (Walling, 2005). Erosion of sediment in catchment systems is a selective process, which tends to mobilise fine material and organic matter preferentially (e.g. Peart and Walling, 1986). Suspended sediment transported by the river is therefore usually enriched in fines and organic content compared with potential source materials. In order to account for the effects of this enrichment on the concentration of fingerprint properties, corrections, based on differences in particle size composition and organic matter content between the suspended sediment and the source materials, were applied to the tracer concentrations used in the mixing model.

The range of tracer properties used in the fingerprinting investigation is listed in Table 2. These included 45 elements analysed by inductively coupled plasma mass spectrometry, after extraction with a simple digest using HNO_3 and HCl, and the artificial radionuclide caesium-137 (^{137}Cs) determined by gamma spectroscopy using a high purity germanium coaxial gamma detector for the source material samples and a well-type germanium detector for the smaller suspended sediment samples. Different fractions of phosphorus were determined using colorimetry after a sodium hydroxide/hydrochloric acid extraction based on the methods of Mehta *et al.* (1954) and Sommers and Nelson (1972), and carbon and nitrogen content was measured using a commercial Carlo Erba NA2500 C/N analyser.

Inductively Coupled Plasma – Mass Spectrometry
Al27, As75, Ba137, Bi209, Cd111, Ce140, Co59, Cr52, Cs133, Cu65, Dy163, Er166, Eu153, Fe56, Gc69, Gd157,Ge72, Hf178, Ho165, K39, La139, Li7, Ln115, Mg24, Mn55, Mo95, Na23, Nd146, Ni60, Pb206, Pb207, Pb208, Pd105, Pr141, Rb85, Sc43, Sm147, Sn118, Sr88, Tb159, Ti47, Ti205, V51, Zn66, Zr90
Gamma-Spectroscopy
Cs137
Colorimetry
Inorganic P, Organic P, Total P
Carlo Erba Analyser
C, N, C/N ratio

Table 2. *The properties used for the fingerprinting (tracing) investigation.*

Land Use and Channel Banks	**Number of Samples**
Cultivated	141
Grassland	313
Woodland	57
Channel Bank	58
Geological Units	**Number of Samples**
Alluvium	26
Gramscatho Beds (*Portscatho Formation*)	80
Gramscatho Beds – conglomerate (*Portscatho Formation*)	12
Granite	177
Hornblende Schist (*Traboe Hornblende-Schist*)	64
Meneage Crush Zone (*Roseland Breccia Formation*)	79
Mylor Beds (*Mylor Slate Formation*)	116
Serpentine (*Peridotite and Serpentinite*)	9
Spilite Lavas (*Roseland Breccia Formation*)	6

Table 3. *The distribution of source material samples. The names of geological units are as shown on the 1:50,000 drift editions of sheets 352 and 359 produced by the British Geological Survey while current nomenclature from Edina Geology Digimap is shown as italicised text in parentheses.*

The potential source materials investigated comprised the major geological units of alluvium, the Gramscatho Beds, conglomerates within the Gramscatho Beds, granite, hornblende schists, rocks in the Meneage Crush Zone, the Mylor Beds, serpentine and spilite lavas. The surface material under the major land-use categories of cultivated areas, grassland (both permanent and temporary pasture) and woodland, and material forming the river channel banks were also investigated as potential sources of suspended sediment transported by the Helford River. A programme of sampling potential source materials in the Helford catchment was carried out during the summer of 2005 and involved collection of 569 samples from sites selected to provide a representative coverage of the different geological units and land-use types and channel banks in the 16 sub-catchments (Table 3, Figure 4). Samples with a mass of *c.* 600 g were collected using a hand trowel from the upper 2 cm of the soil profile and from the surface of actively eroding channel banks. The samples were oven-dried at a temperature of 40°C to remove any moisture, disaggregated using a pestle and mortar and sieved through a 2 mm sieve. The <2 mm fraction was stored for later particle size and gamma spectroscopy determinations and a sub-sample was ground down and sieved at 63 μm for use in other analyses of fingerprint properties.

In order to collect suspended sediment from the study tributaries for analysis of tracer concentrations, Phillips traps (Phillips *et al.*, 2000), scaled down in size to be suitable for small streams, were mounted in the river channel at the outlet above the tidal limit in the 16 sub-catchments (Figure 5). These devices work on the principle that as water flows through the trap, its velocity is slowed and any sediment being carried is deposited so that a time-integrated sample of the transported suspended sediment is collected. The traps were installed in pairs in order to provide back up in the event of nozzle blocking by leaves and other detritus carried in higher flows. They were emptied on a monthly basis and the collected sediment and water mixture was centrifuged at 3,200 rpm for 30 minutes and the sediment recovered was freeze-dried for *c.* 48 hours, sieved to <63 μm and stored for later analysis of tracer concentrations.

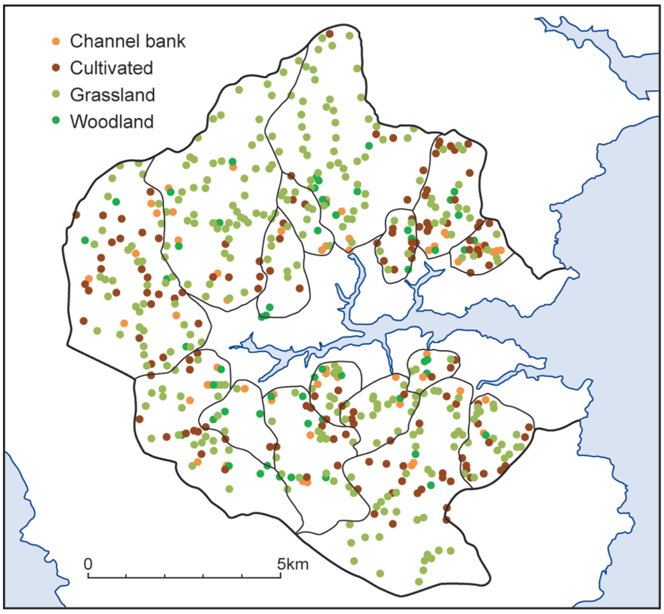

Figure 4. *Distribution of sampling sites for source materials in the study area.*

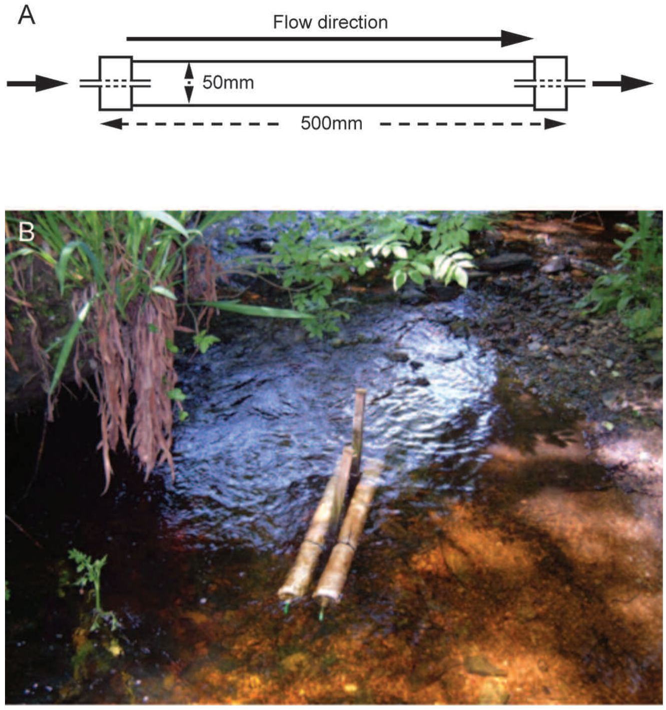

Figure 5. *Phillips traps used to collect suspended sediment. (**a**) Schematic diagram. (**b**) Traps installed in the Trenarth sub-catchment.*

Results

Suspended sediment behaviour and transport

Figures 6 and 7 present the records of suspended sediment concentration and discharge collected for the study year and show that the tributaries of the Helford were characterized by a relatively flashy flow and suspended sediment response to rainfall events. The annual hydrograph comprised a series of short-lived discharge peaks which were associated with spikes in suspended sediment concentration. Examination of individual storm events (Figure 8) reveals that it was common for suspended sediment concentrations to reach a peak before river flows, which suggests that there is a good connection between the river channel and sources of fine sediment in the upstream catchment area, and also that the supply of readily available fine material may become depleted during the course of a storm. Peak suspended sediment concentrations may also decline through a series of closely-spaced discharge events of similar magnitude, as was evident for three storms recorded at Trelowarren during the beginning of November 2005 (Figure 8). This may indicate that the supply of fine sediment in the catchment is limited and becomes depleted during wet spells.

Construction of cumulative load duration curves (Figure 9) highlights that the transport of suspended sediment in the study catchment was biased to higher discharges. This was particularly so for the three southern tributaries where more than 90% of the total load recorded in the study period was moved in less than 10% of the time. For Gweek North and Polwheveral, more than 80% of the load was transported in *c.* 20% of the time, while *c.* 30% of the time was required to transport the same proportion of the load at Gweek West (Figure 9). Not unexpectedly, given the bias of suspended sediment transport to higher flows, monthly loads were highest in the winter period (Figure 10). Monthly suspended sediment loads reached a peak in December 2005 at all monitoring stations, and it was typical for more than 60% of the total load to be carried during the period from the beginning of October 2005 until the end of January 2006. Lowest loads were recorded at most sites in July and August, and accounted typically for less than 2% of total transport, but sediment transport was also relatively low in April 2006 and this month had the lowest suspended sediment load at Gweek West (Figure 10). More variability between tributaries in the pattern of monthly loads was evident for the period after December 2005.

The relationship between suspended sediment transport and runoff in the study catchment is evident from a plot of total monthly loads and average monthly runoff recorded for the six tributaries in each month of the study year (Figure 11). In the period from June until December 2005, sediment transport and runoff were well correlated, so that loads declined with decreasing flows through the summer and early autumn, but

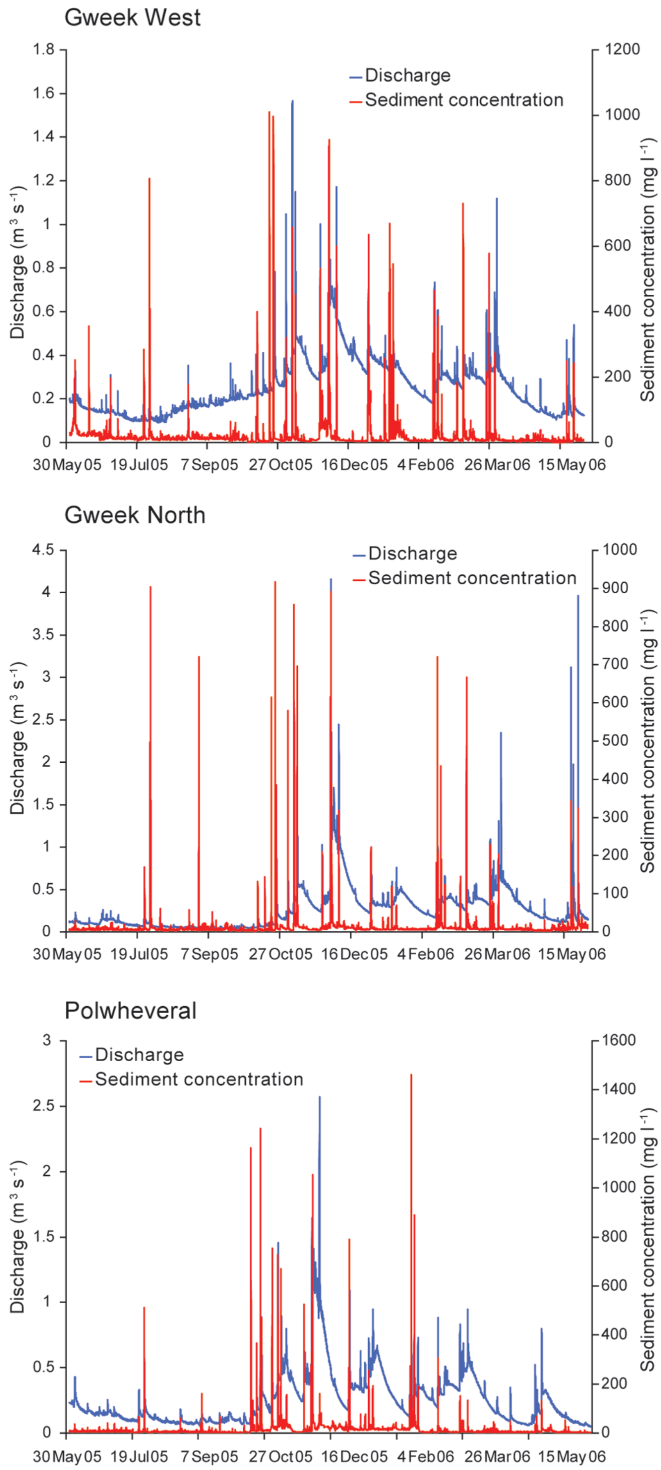

Figure 6. *Suspended sediment and discharge records from tributaries on the northern side of the Helford River.*

exhibited strong increases in proportion to the rising discharge from October to December. The correlation between monthly sediment transport and monthly runoff is much less marked in the period from January to May 2006, since the relatively high average flows in January and March were not mirrored by equivalent increases in total load, and sediment transport in April was considerably less than that in May, despite average discharge being very similar for these two months (Figure 11). A more erratic relationship between sediment load and runoff in the post mid-winter months may reflect an intra-seasonal exhaustion effect whereby wet conditions in the early winter period deplete significantly the fine sediment available to be transported in the late winter period.

Specific suspended sediment yields, expressed as tonnes transported per square kilometre of catchment area per year, differed between the Helford sub-catchments (Figure 12) and ranged from around 30 t km^{-2} a^{-1} in two southern tributaries (Pontsontuel, Gillan-Manaccan) to nearly 17 t km^{-2} a^{-1} for two northern tributaries (Gweek North, Gweek West). These differences do not mirror contrasts in annual discharges (Figure 12) which tend to be higher on the northern than the southern side of the Helford system, again highlighting that sediment transport is not a simple function of river flow.

Extrapolation of the monitored suspended sediment yields,

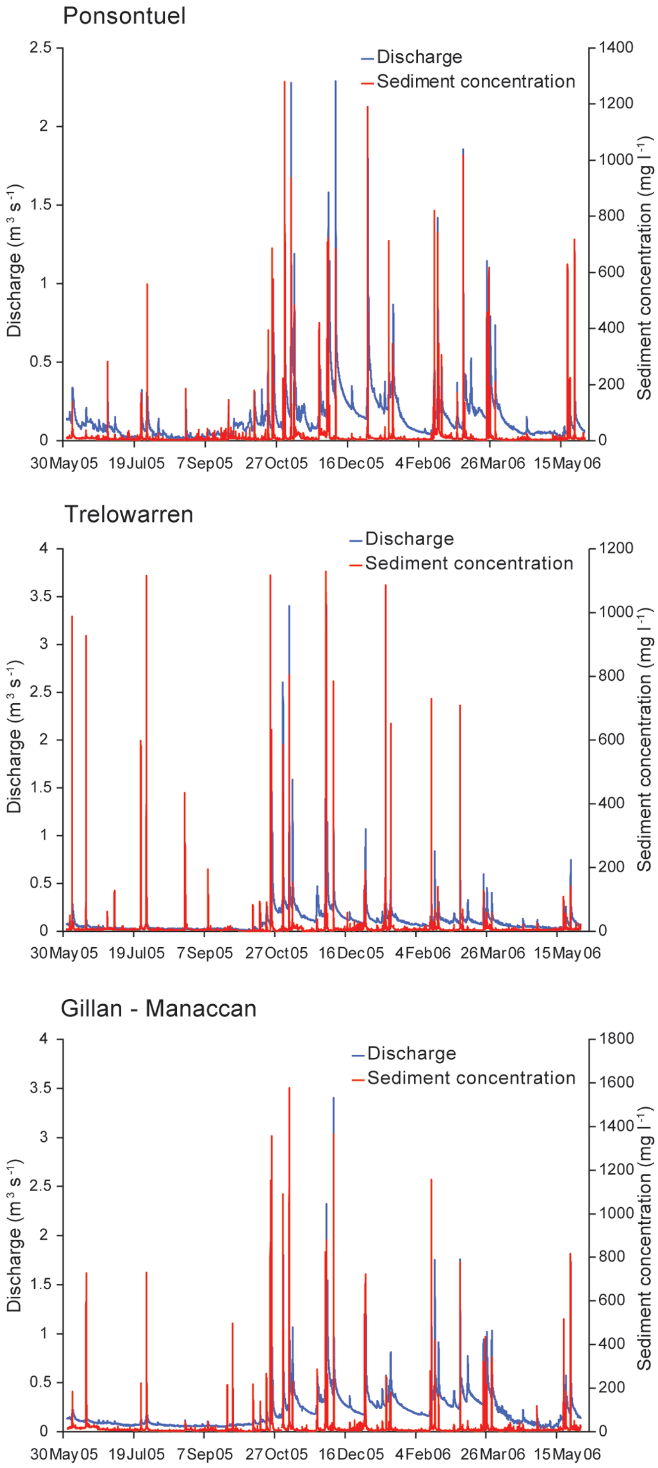

Figure 7. *Suspended sediment and discharge records from tributaries on the southern side of the Helford River.*

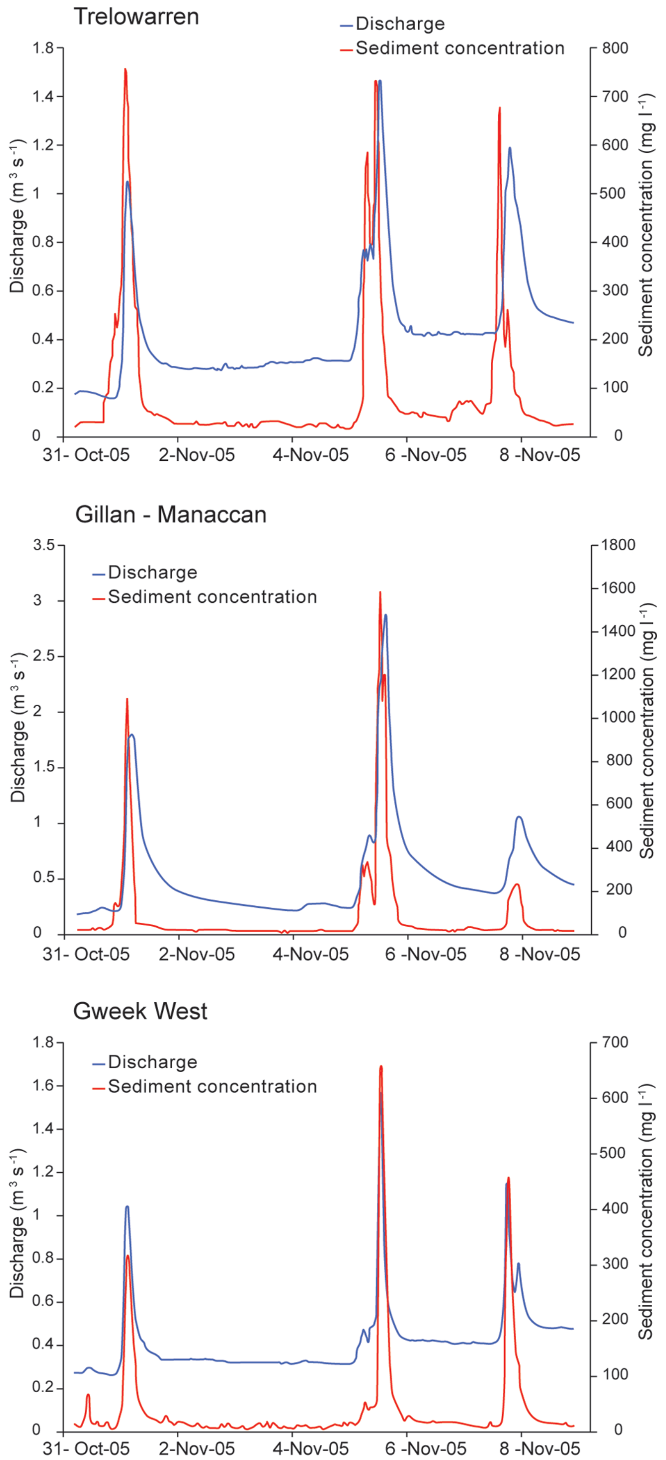

Figure 8. *Examples of responses of suspended sediment concentration and discharge during individual storm events in selected study sub-catchments.*

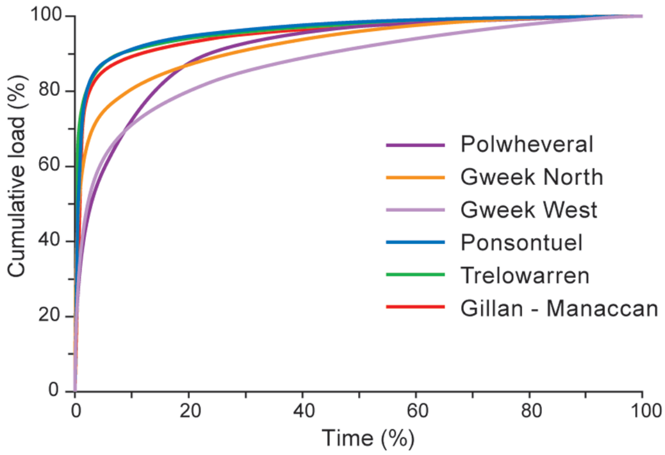

Figure 9. *Cumulative suspended sediment load duration curves for the six largest sub-catchments in the Helford River.*

averaged separately for the northern and southern tributaries, to the unmonitored part of the study area, provides an estimated delivery of suspended sediment to the tidal limit of 2,175 tonnes and an overall specific suspended sediment yield for the catchment of c. 23.5 t km^{-2} a^{-1} in the study period.

Suspended sediment sources

The results of the fingerprinting investigation indicated that the different geological units contributed suspended sediment largely in proportion to the area of the Helford catchment which they occupy (Figure 13). This was especially so for the northern side of the basin where runoff from the major units of the Mylor Beds and the Carnmenellis Granite is estimated to contribute more than 80% of the suspended sediment. In the southern part of the system, however, the sizeable outcrop of serpentine only appears to contribute less than 2% of the suspended sediment, and this may reflect the protective influence of the heathland cover that is commonly found on this rock type.

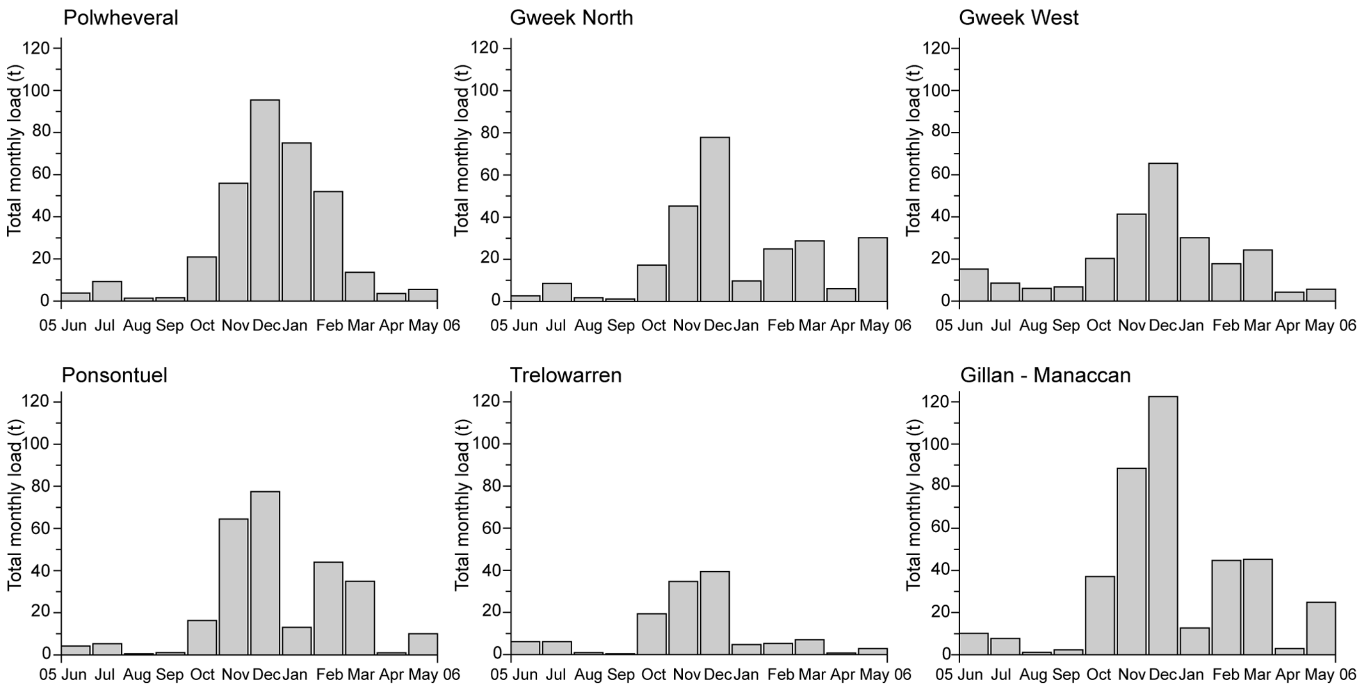

Figure 10. *Monthly suspended sediment loads in the six largest sub-catchments in the Helford River during the study period.*

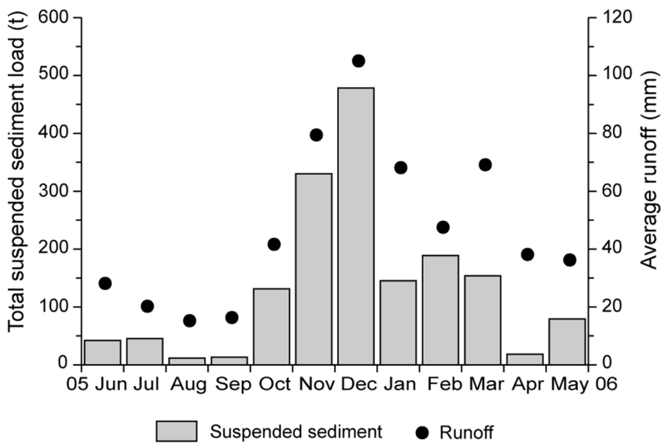

Figure 11. *The relationship between monthly total suspended sediment load and average monthly runoff for the six monitored sub-catchments in the Helford River during the study period.*

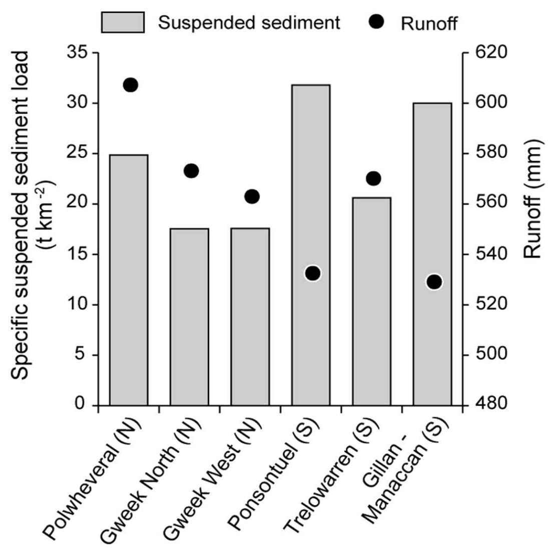

Figure 12. *The relationship between specific suspended sediment yield and runoff for the six monitored sub-catchments in the Helford River.*

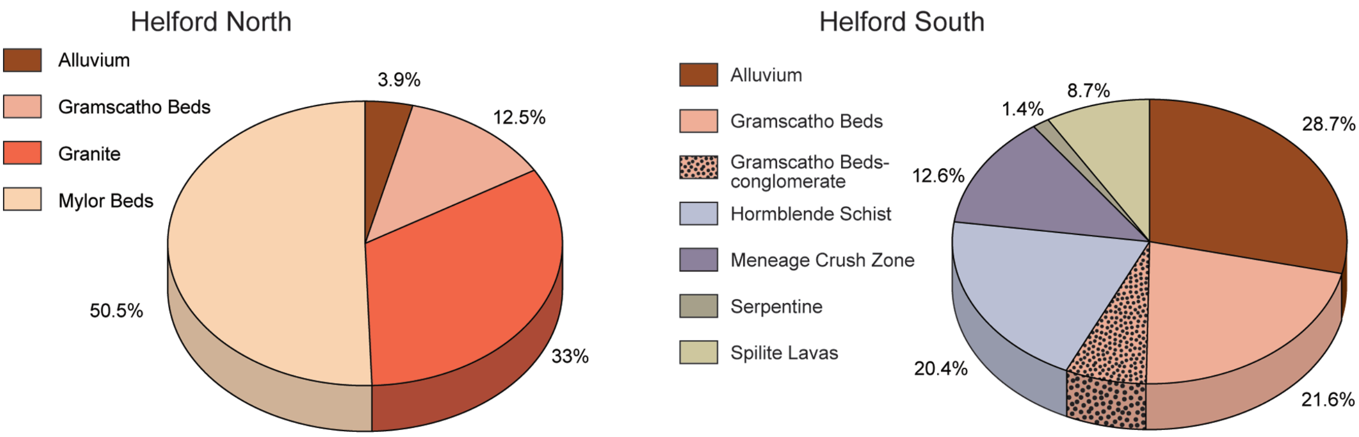

Figure 13. *The contribution of suspended sediment from different geological units on the northern and southern sides of the Helford River.*

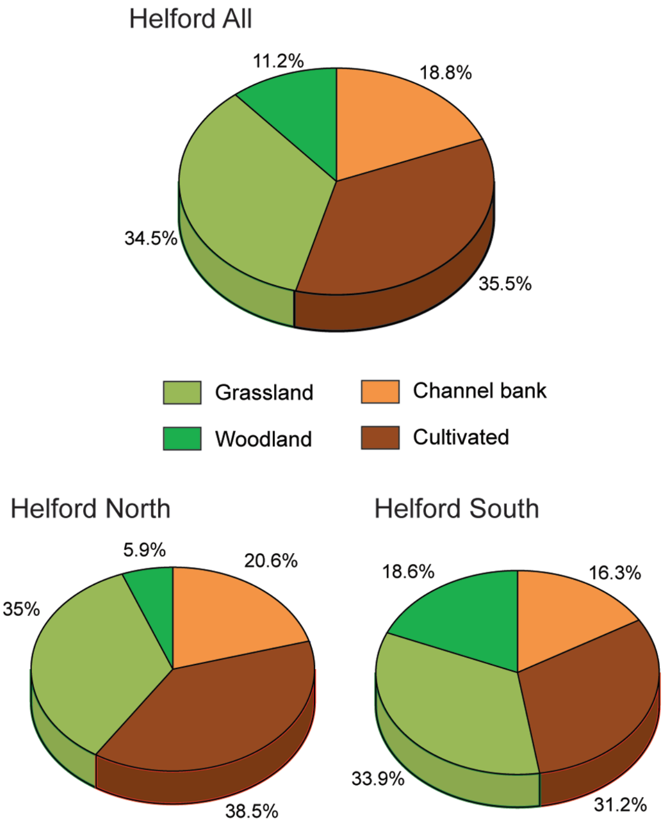

Figure 14. *The contribution of suspended sediment from different land uses and channel banks for the Helford River as a whole and for its northern and southern sides.*

Fingerprinting with respect to surface soil under different land-use and channel bank categories, revealed that permanent and temporary grassland together accounted for *c.* 35% of the suspended sediment delivered to the tidal limit in the catchment as a whole, which is the same as that contributed from cultivated land, although the area under cultivation is considerably smaller than that under grass (Figure 14). Material eroded from channel banks, as opposed to surface erosion of fields, was also shown to be a significant source of suspended sediment, and accounted for nearly 19% of the total transport. Although woodland cover is not very extensive in the Helford catchment, fingerprinting results suggested that it contributed more than 11% of the transported sediment, which may be related to its location on the steeper slopes. The importance of land-use and channel bank sources is broadly similar for tributaries on the northern and southern sides of the Helford, although woodland makes a somewhat greater, and channel banks a somewhat lesser, contribution in the south compared with the north (Figure 14). Considerable variation in the relative importance of different land-use and channel bank sources was evident between the sub-catchments of the Helford system (Figure 15). Grassland was estimated to contribute a minimum of *c.* 6% of the suspended sediment transport but accounted for at least 20% at most sites and up to just under 80% for the small Helford tributary. The contribution from the other categories fell to a minimum of less than 1% in some sub-catchments, but reached maxima of 31% for woodland in Frenchman's Creek, 55% for channel banks in Gweek North, and more than 80% for cultivated land in Gweek West.

Examination of the fingerprinting results for individual months suggests there is some inter-annual variability in the contribution to suspended sediment transport made by particular land-use and channel bank sources (Figure 16). For

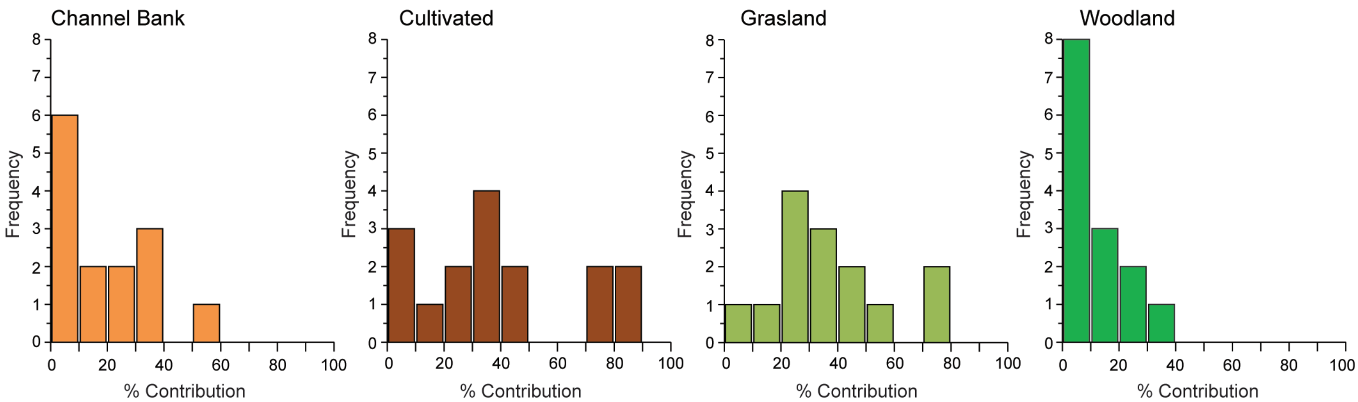

Figure 15. *Variation between sub-catchments of the Helford River in the contribution of suspended sediment from different land uses and channel banks.*

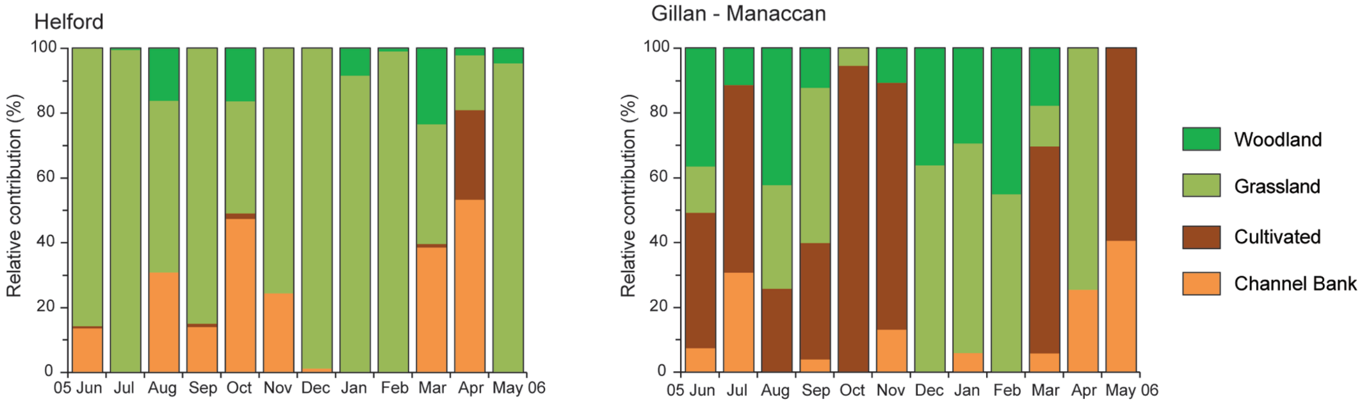

Figure 16. *Temporal variation in the contribution of suspended sediment from different land uses and channel banks for two sub-catchments of the Helford River.*

some sub-catchments, a single land use is dominant in most months but other sources may be significant at other times of the year. The small Helford tributary provides an example of this source behaviour. Grassland dominated as the source of suspended sediment for much of the study period, but channel bank erosion contributed around 50% of the sediment in some months in the autumn of 2005 and spring of 2006. In other tributaries, however, the pattern of source contributions through time appears to be complex. For example, the source of suspended sediment in the Gillan-Manaccan sub-catchment was dominated by cultivated land in some months and grassland in others, but woodland and channel banks also made significant contributions at different times throughout the study period.

An estimate of the amount of suspended sediment delivered to the tidal limit of the study area in the study year from particular sources may be obtained by combining the monitoring and fingerprinting elements of the investigation (Figure 17). In terms of the geological units, the area underlain by the Mylor Beds provided the most important source and yielded more than 500 tonnes of suspended sediment, whereas the Carnmenellis Granite, Gramscatho Beds and alluvium were also major sources and each yielded more than 300 tonnes. With respect to different land uses and channel banks, cultivated areas provided most suspended sediment but only exceeded grassland by a small amount and both types yielded more than 700 tonnes in comparison with 400 tonnes which originated from channel bank erosion and more than 200 tonnes from woodland areas.

Discussion

The behaviour of suspended sediment concentrations during storm events in the Helford River is very similar to that recorded in other catchments of South-West England (e.g. Walling, 1974; Walling and Webb, 1987). Hysteretic effects, whereby concentrations on the rising limb of storm hydrographs are greater than those at corresponding flow levels on the falling limb, are typical and imply that suspended sediment is a non-capacity load and the sources supplying fine material to the river channel are subject to exhaustion during storm events. There is also some evidence of exhaustion of sediment sources during sequences of storm events. However, as results from a relatively steep agricultural catchment in Devon have shown, this effect may also be generated by greater dilution of fine sediment delivered in storm runoff, as the pre-storm baseflow in the river channel increases during a series of closely-spaced events (Walling and Webb, 1982). It is likely that the response of suspended sediment concentrations in a given storm in the Helford River will depend in a complex manner on the magnitude and intensity of the generating rainfall, the extent and distribution of the source areas producing surface runoff and the conditions antecedent to the event.

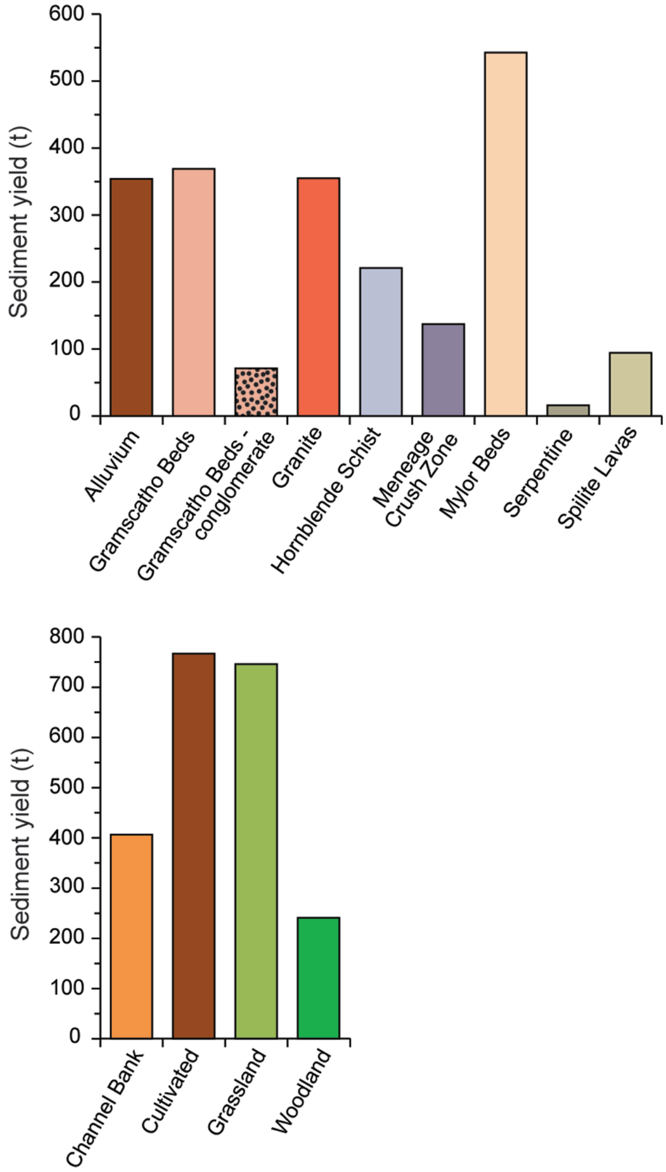

Figure 17. *The estimated amount of suspended sediment delivered to the tidal limit of the Helford River from different geological units, land uses and channel banks.*

The importance of high flows in transporting suspended sediment in the Helford River is also evident. In the monitored southern tributaries, more than 90% of the suspended sediment load was removed in less than 10% of the time, which is typical of other catchments in South-West England (e.g. Webb and Walling, 1982, 1984). Although still dominated by high discharges, suspended sediment transport was a somewhat more protracted process for tributaries monitored on the northern side of the Helford, which may reflect their somewhat larger size. The bias of suspended sediment transport to higher discharges accounts for the higher loads recorded during the winter months when river flows are at their greatest. However, an intra-seasonal exhaustion effect also appears to exist, whereby runoff in the early winter months is associated with greater suspended sediment transport than in the late winter period. This phenomenon has also been recorded for the River Exe system, where sediment loads in the months from October to December were higher on average than those in the months January to December, despite equivalent volumes of flow in the two periods (Harlow *et al.*, 2006).

The specific suspended sediment yields recorded in the tributaries of the Helford River in the study period are not atypical of those found more generally in British rivers (Walling and Webb, 1981) and lie within the range of 4 - 58 t km^2 a^{-1} reported for the Exe Basin of Devon and Somerset (Walling and Webb, 1987). Specific suspended sediment yields on the northern side of the catchment averaged *c.* 20 t km^2 a^{-1} compared with *c.* 27.5 t km^2 a^{-1} on the southern side. The lower yields for the northern tributaries, despite somewhat higher volumes of runoff, suggest that the substantial outcrop of granite on this side of the Helford River may limit the production and mobilisation of fine-grained river sediment.

Previous longer-term studies of the rivers of South-West England (Webb and Walling, 1982; Harlow *et al.*, 2006) have demonstrated considerable inter-annual variability in the magnitude of suspended sediment transport which begs the question of how representative the results from a single study year for the Helford River can be expected to be. Long-term flow records available from the National River Flow Archive (*http://www.ceh.ac.uk/data/nrfa/index.html*) for the River Hayle at St Erth and the River Fal at Tregony, which drain areas close to the Helford system in West Cornwall, suggest that the study period was one of lower than average flows. For the River Hayle at St Erth, the 12 month period from 1 June 2005 to 31 May 2006, had a mean flow that was 80.1% of the average recorded for this period between 2000 and 2010, and 77.4% of the long-term mean flow recorded at this station in the years from 1957 to 2010. The equivalent figures for the River Fal at Tregony were 78.0% and 76.5%, and the long term average in this case was based on gauging from 1978 to 2010. This suggests that the amount of sediment delivered to the tidal limit of the Helford River calculated in the present study is likely to be an underestimate of the longer term average value.

As in other tracing studies carried out in South-West England (e.g. Collins *et al.*, 1997, 1998a, b; Walling and Woodward, 1995; Walling, 2005), the fingerprinting investigation of the Helford River, in general, produced good discrimination between potential sediment sources categorized according to geological unit and land-use type.

There was little evidence of large differences between the different geological units in the study catchment regarding their potential for the production of suspended sediment per unit area, with the exception of the outcrops of serpentine, and to a lesser extent granite, for which the fingerprinting study suggested the contribution of material was less than that expected from the area of outcrop. This lack of differences in contribution from the individual geological units is perhaps unsurprising, given the relatively similar age and tectonic history of the rocks underlying the Helford catchment, and contrasts between units were much less marked than those identified in fingerprinting studies undertaken in the Exe catchment where a much greater range of rocks in terms of induration are present, and areas underlain by Triassic (Walling and Woodward, 1995) and Permian (Collins *et al.*, 1998a) strata were found to be substantially more important as sources of suspended sediment than those underlain by older Devonian and Carboniferous rocks and younger Cretaceous and Eocene lithologies.

The fingerprinting investigation suggested that more than one third of the suspended sediment generated in the Helford River originated from cultivated land which occupied less than one quarter of the catchment area. In this respect, the study area is similar to other catchments in South-West England, where sediment fingerprinting studies have also shown that cultivation is associated with relatively high specific suspended sediment yields (Table 4) which arise through the exposure of bare tilled soils to rainsplash and surface runoff (Collins *et al.*, 1997). Furthermore, the growing of potato and early flower crops in the study area is likely to promote increased soil erosion (Harrod, 1994). Temporary and permanent grassland was also a significant source of suspended sediment in the study catchment, as has been found to be the case in other river systems of the South-West peninsula (Table 4), especially where high stocking densities encourage poaching of the ground (Walling, 2005). In terms of the total amount delivered to the tidal limit of the study catchment, grassland contributed almost as much suspended sediment as cultivated land, although the area under grass was approximately three times greater than that under crops, so specific suspended sediment yields were correspondingly three times lower. Areas under woodland have been shown in other catchments of South-West England (Table 4) to be a minor source of suspended sediment reflecting their relatively limited extent and the general lack of surface runoff and sediment generation from land with a forest or

Catchment / **Source Category**	**Upper Torridge at Rockhay Bridge ($258 km^2$)**	**Dart at Bickleigh ($46 km^2$)**	**Exe at Thorverton ($601 km^2$)**
Cultivated	28.0 (16.0)	14.1 (11.9)	20.4 (9.2)
Grassland	47.0 (80.0)	77.9 (83.5)	71.7 (86.6)
Woodland	2.0 (4.0)	4.5 (4.6)	2.6 (4.2)
Channel Bank	23.0	3.5	5.3
Reference	Walling (2005)	Collins *et al.* (1997)	Collins *et al.* (1998b)

Table 4. *Percentage contribution of suspended sediment from different sources in selected catchments of South-West England. Figures in parentheses indicate the percentage of different land-use types in the catchments.*

wooded cover (Walling, 2005). The proportion of the Helford catchment that is wooded is small (<4%) but the fingerprinting study suggested this land use contributed more than 11% of the suspended sediment delivered to the tidal limit for the study area as a whole and over 18% for the southern tributaries. This may reflect the fact that the woodland, especially on the southern side of the Helford, is concentrated in riparian areas and therefore susceptible to erosion during overbank flooding, and also is often located on steeper land unsuitable for agricultural use, which increases the potential for surface erosion. Channel bank erosion also contributed a significant proportion of the suspended sediment (>18%) in the Helford catchment. In this respect, the findings from the present study are similar to those from the Upper Torridge (Walling, 2005), where channel erosion accounted for 23% of the suspended sediment delivered to the catchment outlet and was attributed to a flashy hydrological response and high drainage density of the catchment under wet conditions, the high extent of actively eroding river channel and the trampling and degradation of the banks by livestock, and the presence of ditches associated with agricultural systems.

The present study also revealed considerable spatial contrasts between the different tributaries of a relatively small catchment in the importance of different land-use types and channel banks in generating suspended sediment. This complexity was further compounded by significant temporal variability in the importance of suspended sediment contributions from different land uses and channel banks which was evident in the results of fingerprinting suspended sediment collected at monthly intervals. Temporal variation in sediment sources has also been identified in other studies in South-West England, and has been related to seasonal and inter- and intra-storm variations in catchment condition and hydrological behaviour (e.g. Collins *et al.*, 1997, 1998a, b; Walling and Woodward, 1995; Walling, 2005). However, the pattern of temporal behaviour in the Helford River was not consistent between the individual sub-catchments so that in some tributaries a particular land-use remained a dominant source of suspended sediment throughout the study period, whereas in others different sources dominated at different times of the study year.

Overall, the present study has highlighted considerable spatial and temporal complexity within a relatively small catchment not only in suspended sediment behaviour and transport but also in the sources of this material.

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REFERENCES

COLLINS, A.L. and WALLING, D.E. 2002. Selecting fingerprint properties for discriminating potential suspended sediment sources in river basins. *Journal of Hydrology,* **261**, 218-244.

COLLINS, A.L. and WALLING, D.E. 2004. Documenting catchment suspended sediment sources: problems, approaches and prospects. *Progress in Physical Geography,* **28**, 159-196.

COLLINS, A.L., WALLING, D.E. and LEEKS, G.J.L. 1997. Source type ascription for fluvial suspended sediment based on a quantitative composite fingerprinting technique. *Catena,* **29**, 1-27.

COLLINS, A.L., WALLING, D.E. and LEEKS, G.J.L. 1998a. Use of composite fingerprints to determine the provenance of the contemporary suspended sediment load transported by rivers. *Earth Surface Processes and Landforms,* **23**, 31-52.

COLLINS, A.L., WALLING, D.E. and LEEKS, G.J.L. 1998b. Fingerprinting the origin of fluvial suspended sediment in larger river basins: combining assessment of spatial provenance and source type. *Geografiska Annaler,* **79A**, 239-254.

DEFRA 2004. The June Agricultural Census. Department for Environment, Food and Rural Affairs, York. *http://farmstats.defra.gov.uk/cs/farmstats_data/DATA/postcode/postcode_repop_query.asp*, last accessed on 22nd November 2006.

HARLOW, A., WEBB, B.W. and WALLING, D.E. 2006. Sediment yields in the Exe Basin: a longer-term perspective. In: ROWAN, J.S, DUCK, R.W. and WERRITTY, A. (Eds), *Sediment Dynamics and the Hydromorphology of Fluvial Systems (Proceedings of a symposium held in Dundee, UK, July 2006), IAHS Publication No. 306*. International Association of Hydrological Sciences Press, Wallingford, 12-20.

HARROD, T.R. 1994. Runoff, soil erosion and pesticide pollution in Cornwall. In: RICKSON, R.J. (Ed.), *Conserving Soil Resources European Perspectives Selected papers from the First International Congress of the European Society for Soil Conservation*. CAB International, Wallingford, 105-115.

HARROD, T.R. and THEURER, F.D. 2002. Sediment. In: HAYGARTH, P.M. and JARVIS, S.C. (Eds), *Agriculture, Hydrology and Water Quality*. CABI Publishing, Oxfordshire, 155-170.

HUGHES, S.H. 1999. The geochemical and mineralogical record of the impact of historical mining within estuarine sediments from the upper reaches of the Fal Estuary, Cornwall, UK. *Special Publication of the International Association of Sedimentologists,* **28**, 161-168.

LEVERIDGE, B.E., HOLDER, M.T. and GOODE, A.J.J. 1990. *Geology of the country around Falmouth*. Memoir for the 1:50,000 geological sheet 352 (England and Wales). HMSO, London.

MEHTA, N.C., LEGG, J.O., GORING, C.A.I. and BLACK, C.A. 1954. Determination of organic phosphorus in soils: I. Extraction method. *Soil Science Society of America Journal,* **18**, 443-449.

MET OFFICE. 2000. Map of average autumn rainfall (1971-2000). *http://www.metoffice.com/climate/uk/location/southwestengland/images/LTA_7100_rr_15.gif*, last accessed on 22nd November 2006.

PEART, M. and WALLING, D.E. 1986. Fingerprinting sediment source: The example of a drainage basin in Devon, UK. In: HADLEY, R.F. (Ed.), *Drainage Basin Sediment Delivery (Proceedings Albuquerque Symposium, August 1986), IAHS Publication No. 159*. International Association of Hydrological Sciences Press, Wallingford, 41-55.

PHILLIPS, J.M., RUSSELL, M.A. and WALLING, D.E. 2000. Time-integrated sampling of fluvial suspended sediment: a simple methodology for small catchments. *Hydrological Processes,* **14**, 2589-2602.

PIRRIE, D., CAMM, G.S., SEAR, L.G. and HUGHES, S.H. 1997. Mineralogical and geochemical signature of mine waste contamination, Tresillian River, Fal Estuary, Cornwall, UK. *Environmental Geology,* **29**, 58-65.

PIRRIE, D., POWER, M.R., PAYNE, A., CAMM, G.S. and WHEELER, P.D. 2000. Impact of mining on sedimentation; the Camel and Gannel estuaries, Cornwall. *Geoscience in South-West England,* **10**, 23-28.

PIRRIE, D., POWER, M.R., ROLLINSON, G., CUNDY, A.B. and WATKINS, D.C. 2002a. Impact of mining on the sediment geochemistry and mineralogy of the Helford River, Cornwall. *Geoscience in South-West England,* **10**, 323-328.

PIRRIE, D., POWER, M.R., WHEELER, P.D., CUNDY, A., BRIDGES, C. and DAVEY, G. 2002b. Geochemical signature of historical mining: Fowey Estuary, Cornwall, UK. *Journal of Geochemical Exploration,* **76**, 31-43.

PIRRIE, D., POWER, M.R., ROLLINSON, G., CAMM, G.S. HUGHES, S.H., BUTCHER, A.R. and HUGHES, P. 2003. The spatial distribution and source of arsenic, copper, tin and zinc within surface sedimen*ts of the Fal Estuary, Cornwall, UK. Sedimentology, 5***0**, 579-595.

RICHARDS, K.S. 1979. Channel adjustment to sediment pollution by the china clay industry in Cornwall, England. In: RHODES, D.D. and WILLIAMS, G.P. (Eds), *Adjustments of the fluvial system: a proceedings volume of the tenth Annual Geomorphology Symposia series held at Binghamton, New York, September 21 22*, 1979. Kendall-Hunt Pub. Co., Dubuque, Iowa, 309-331.

ROLLINSON, G.K., PIRRIE, D., POWER, M.R., CUNDY, A. and CAMM, G.S. 2007. Geochemical and mineralogical record of historical mining, Hayle Estuary, Cornwall, UK. *Geoscience in South-West England,* **11**, 326-337.

SOMMERS, L.E. and NELSON, D.W. 1972. Determination of total phosphorus in soils: A rapid perchloric acid procedure. *Soil Science Society of America Proceedings,* **36**, 902-904.

WALLING, D.E. 1974. Suspended sediment and solute yields from a small catchment prior to urbanization. In: GREGORY, K.J. and WALLING, D.E. (Eds), *Fluvial Processes in Instrumented Watersheds, Institute of British Geographers Special Publication No. 6*. Institute of British Geographers, London, 169-192.

WALLING, D.E. 2005. Tracing suspended sediment sources in catchments and river systems. *Science of the Total Environment,* **344**, 159-184.

WALLING, D.E. and WEBB, B.W. 1981. Water quality. In: LEWIN, J. (Ed.), *British Rivers*. George Allen and Unwin, London, 126-169.

WALLING, D.E. and WEBB, B.W. 1982. Sediment availability and the prediction of storm-period sediment yields. In: WALLING, D.E. (Ed.), *Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield (Proceedings of the Exeter Symposium, July 1982), IAHS Publication No. 137*. International Association of Hydrological Sciences Press, Wallingford, 327-337.

WALLING, D.E. and WEBB, B.W. 1987. Suspended load in gravel-bed rivers: UK experience. In: THORNE, C.R., BATHURST, J.C. and HEY, R.D. (Eds), *Problems of Sediment Transport in Gravel-Bed Rivers*. J. Wiley and Sons, London, 691-732.

WALLING, D.E. and WOODWARD, J.C. 1995. Tracing sources of suspended sediment in river basins: A case study of the River Culm, Devon, UK. *Marine and Freshwater Research,* **46**, 327-336.

WALLING, D.E., COLLINS, A.L. and MCMELLIN, G.K. 2003. A reconnaissance survey of the source of interstitial fine sediment recovered from salmonid spawning gravels in England and Wales. *Hydrobiologia,* **497**, 91-108.

WEBB, B.W. and 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. and WALLING, D.E. 1984. Magnitude and frequency characteristics of suspended sediment transport in Devon rivers. In: BURT, T.P. and WALLING, D.E. (Eds), *Catchment Experiments in Fluvial Geomorphology*. Geo-Books, Norwich, 399-415.

YIM, W.W.-S. 1981. Geochemical investigations on fluvial sediments contaminated by tin-mine tailings, Cornwall, England. *Environmental Geology,* **3**, 245-256.