Scale-related sediment and phosphorus transfers in small agricultural catchments

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Abstract Gaining a better understanding of the processes and linkages operating in agricultural catchments is essential in understanding how diffuse sources of pollution influence the water quality of fluvial systems. One of the key limitations is the lack of available data at a range of spatial scales, which is necessary in order to improve process understanding and model development. Carefully designed field-based research has the potential to improve predictions of water quality in agricultural catchments, which is particularly important given the context of changing climate and land use. Event-based fluxes of sediment and phosphorus were monitored at different scales in a first-order agricultural catchment in Herefordshire, UK, and the data have enabled characterisation of their behaviour and identification of relationships at various scales from hillslope patches of 60 m length to a 30 ha first-order catchment. The results shown here indicate the differing behaviour of both sediment and phosphorus over six events throughout two hydrological years between two scales of observation: the hillslope and the catchment.

Key words field monitoring; catchment; sediment; phosphorus; soil erosion; scale

INTRODUCTION AND BACKGROUND

As the limiting nutrient in many rivers and lakes, inputs of phosphorus (P) from agricultural sources are of concern in relation to eutrophication (Moss *et al.*, 2005). Many agricultural catchments now have high soil P contents, as a result of high application rates in manures and fertilizers (Withers *et al.*, 2001). Phosphorus is transferred through hillslopes to streams in dissolved form or in association with sediment (Haygarth *et al.*, 2000), for which hydrology is both the driver and the carrier (Haygarth & Jarvis, 1999). In addition to the issues of soil erosion and sedimentation, therefore, the transfer of sediment is also of concern in the context of nutrient delivery. As farming practices adapt to the pressures of: (a) climate change, which may produce changes in farm land use, crop types, timing and patterns, and (b) environmental sustainability, which may effect changes in farm-scale management, including the use of tramlines, hedgerows, ponds and cover crops (Heathwaite *et al.*, 2005b), the pathways and quantities of water, sediment and P moving from agricultural land into the fluvial system are likely to change. However, it is not yet possible to assess the likely impact of potential changes. The main reason for this is that the processes of sediment and P transfer are not well understood over the range of scales needed for appropriate modelling and management applications (Beven *et al*., 2005).

Much recent work has been carried out into the issue of sediment and P dynamics (e.g. Dils & Heathwaite, 2000; Scanlon *et al*., 2004; Kleinman *et al*., 2006), and as a result, certain aspects have been well documented (e.g. the pathways and mechanisms of detachment and transport), but there are still some major knowledge gaps. These include quantification of transfer and delivery, poor understanding of scale issues and a lack of available data at appropriate scales for modelling, especially at high resolutions (Brazier *et al*., 2005; Heathwaite *et al*., 2005a). The scale issues include poor comprehension of processes operating at scales between the hillslope plot and the catchment, knowledge of the linkages between scales of observation, and little knowledge of whether data can be transferred across scales (Kirkby *et al*., 1996; Parsons *et al*., 2006; Brazier. *et al*., 2007). Without understanding how information changes with spatial scale, it is difficult to assess the significance of field-based data and the uncertainty of its application to modelling and management scenarios at different spatial scales.

The issues of scale can all be partially tackled by the application of focused field monitoring studies targeted at a range of scales to provide appropriate data sets to explore these issues. The recent emphasis on modelling rather than monitoring based studies for researching sediment and P transfer (Brazier, 2004), has led to a lack of appropriate data from which to develop, calibrate and validate models. Further field studies are necessary to increase sediment and P process understanding over a range of scales, and allow suitable management strategies to be developed. The aim of this research was therefore to carry out field-based monitoring at a range of scales within a small first-order agricultural catchment, in order to generate a data set from which to characterise sediment and P behaviour and investigate linkages between spatial scales to further understanding of scale-related sediment and P transfers.

STUDY SITE

The research was carried out at Rosemaund, Herefordshire (OS Grid Reference SO565480) (Fig. 1). The Jubilee catchment (30.6 ha), situated within the ADAS Rosemaund experimental farm, is drained by a first-order stream, a tributary of the River Lugg, which flows into the River Wye. The use of this catchment allowed study of sediment and nutrient dynamics at a site where upstream and point source impacts are minimal, and provided access to detailed current and historical contextual data. In addition, existing field monitoring infrastructure and the small size of the catchment allowed monitoring and observation throughout the site. The catchment has a mean annual rainfall of approximately 660 mm, with slopes of less than 5°, and silty clay loam soils (Bromyard and Middleton series) that are prone to surface runoff and cracking and are widely underdrained, and used for mixed agriculture, principally grazing and winter cereals. For further details on the catchment see Chapman *et al*. (2005), Hodgkinson *et al*. (1998) and Williams *et al*. (1996).

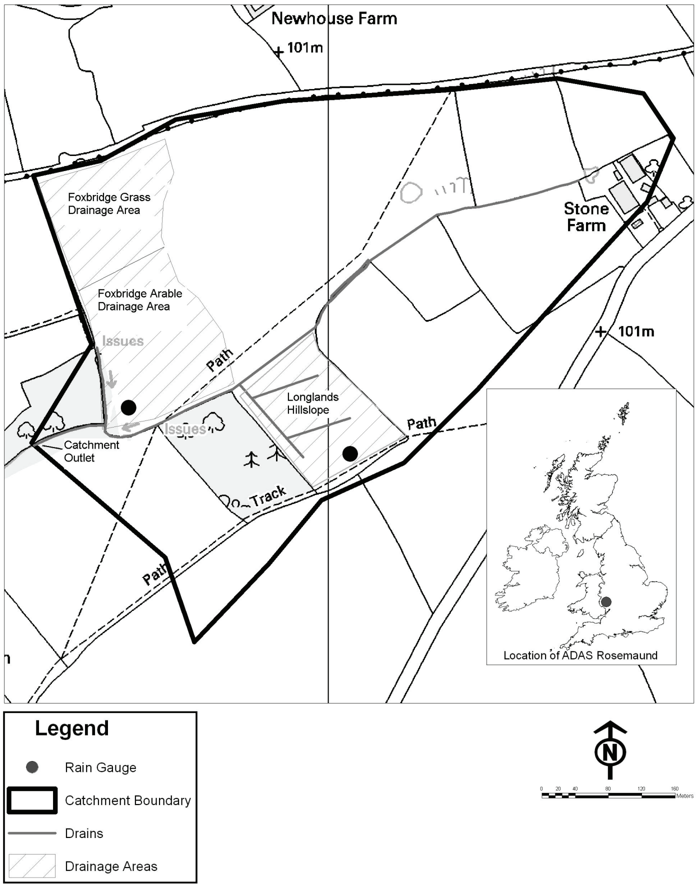

Fig. 1 Ordnance Survey map of the Jubilee catchment, Rosemaund, Herefordshire, showing the location of the study site and the scales of observation and monitoring.

METHODS

Field work

The Jubilee catchment (30.6 ha) was monitored continuously for flow and sediment dynamics at five locations, using stage and turbidity recorders which logged data at 15 min intervals at calibrated flow monitoring locations (weirs and flumes). Stage data were converted to discharge in L s^{-1} using standard calibrations, and turbidity data were converted to suspended sediment (SS) concentrations in mg L^{-1} using calibrations obtained from SS monitoring data. The monitoring locations were selected to represent different scales of observation, and included a 1.9 ha arable hillslope, a 2.5 ha arable drainage area, and a 3.7 ha grass drainage area (Fig. 1). The hillslope and fields were monitored at three subsurface drain outfalls, and the hillslope was also monitored at a surface flume, which drained surface runoff from the hillslope via a perforated plastic pipe installed at approximately 10 cm below the surface at the base of the hillslope. Hillslope flow from the flume was directly connected to the stream, but no further hillslope flow inputs to the stream were observed at any point throughout the monitoring period. Point samples were collected for suspended sediment and P analysis during hydrological events using automated pump sampling. During events, a number of hillslope patches were also monitored using manual point discharge measurements and sample collection. Rainfall data on a 15 min or breakpoint time step were collected using a series of raingauges located throughout the catchment (Fig. 1). Additional monitoring was also carried out for soil moisture, soil particle size and soil P concentration data.

Analytical procedures

Water samples were analysed for SS, total P (TP) and total filterable P ($TP_{<0.45\mu m}$). For SS analysis, samples of 150 ml were filtered through pre-weighed 0.45 µm Whatman nylon filters, and filters were then dried at 105°C before being re-weighed. For TP analysis, 10 ml aliquots of sample were digested using autoclave digestion at 121°C for 30 mins. Samples for $TP_{<0.45\mu m}$ were first filtered through 0.45 µm Whatman cellulose nitrate filters. Analysis of P concentrations was then determined colorimetrically (Murphy & Riley, 1962) using flow injection analysis, and the particulate P fraction ($TP_{>0.45\mu m}$) was determined by difference ($TP_{>0.45\mu m} = TP - TP_{<0.45\mu m}$). Samples were stored in polyethylene bottles, and refrigerated prior to analysis.

OBSERVATIONS AND ANALYSIS

During two hydrological years of monitoring (2004–2005 and 2005–2006), six P transfer events were observed at multiple scales of observation. Figure 2 shows the rainfall and flow for the hillslope and catchment scales for both hydrological years monitored. Rainfall, flow, SS and P characteristics for each event were defined at each scale of observation, and used to: (a) characterise the behaviour of each scale of observation, (b) develop relationships describing the behaviour of each scale in relation to rainfall, flow, hydrology, sediment and P, and (c) develop relationships linking the characteristics of the different scales of observation. Table 1 shows the dates of occurrence and the rainfall characteristics of each event monitored. The event characteristics for the hillslope and catchment scales are discussed in the following three sections, with the dynamics of event VI shown as examples.

Table 1 Rainfall characteristics for P transfer events monitored in 2004–2005 and 2005–2006.

Event	Date	Rainfall: Total (mm)	Peak intensity (mm h^{-1})	Duration (h)
I	6/4/2005	6.0	3.2	9.00
II	18/4/2005	11.4	4.0	23.50
III	2/11/2005	8.2	3.2	10.25
IV	1/12/2005	48.8	11.2	105.75
V	15/2/2006	10.2	2.4	68.00
VI	8/3/2006	18.4	4.0	77.25

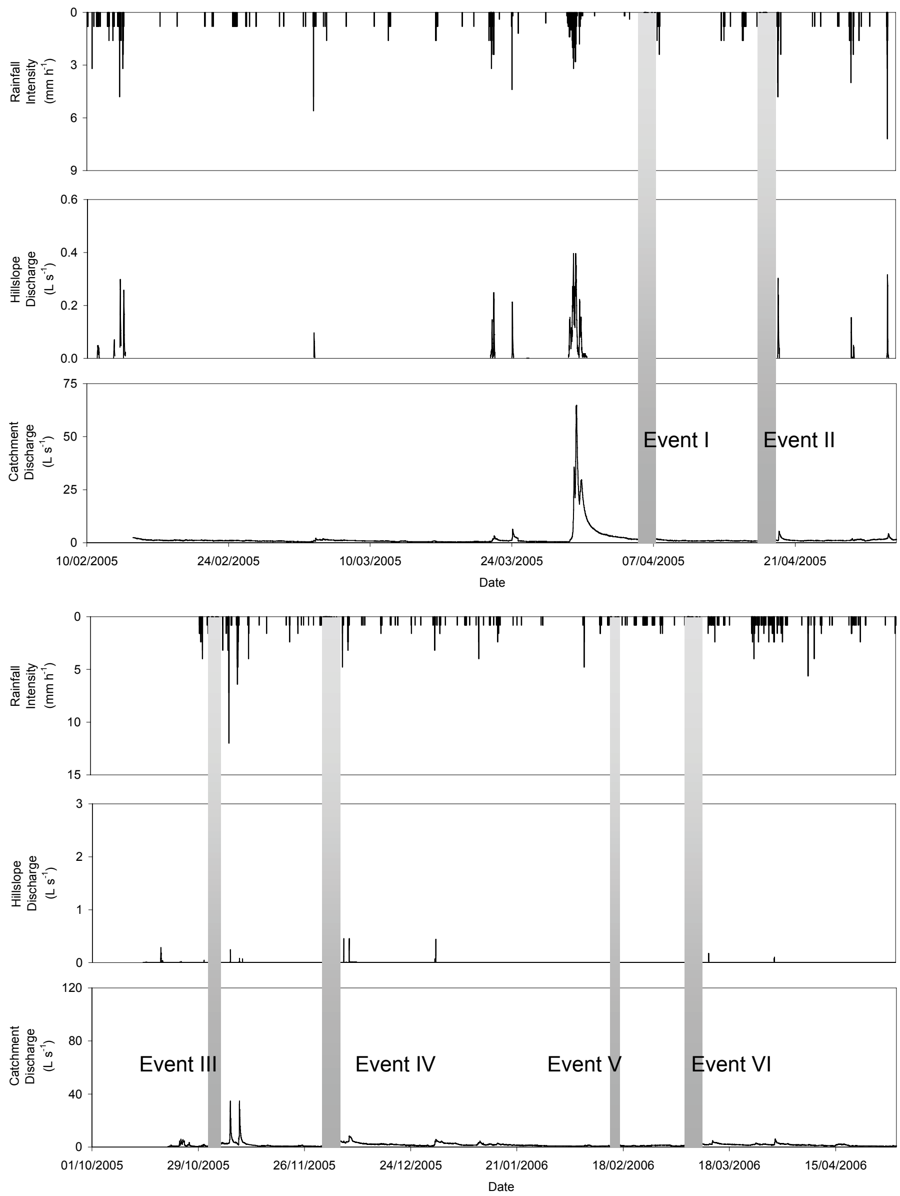

Fig. 2 Rainfall and flow recorded on a 15 min time step for the 1.9 ha Longlands hillslope and the 30.6 ha Jubilee catchment, for: (a) the 2004–2005 and (b) the 2005–2006 hydrological year. Shaded bands show monitored P transfer events.

Hydrology

Figure 3 indicates that flow on the hillslope is much flashier in response to rainfall than flow at the catchment scale, with peak lag times between 0.5 and 2.5 h shorter, and much shorter flow hydrograph durations (Table 2). In two of the six P events monitored, no flow response was observed on the hillslope (events III and V). Peak discharge recorded in the hillslope flume was generally below the stream baseflow level of approximately 1 L s^{-1}, although in event IV, the largest event monitored in the two hydrological years, flow was of a much greater magnitude and comparable to streamflow in the smaller events. Discharge yields from the hillslope contributed up to 1.3% of the flow discharged through the catchment outlet in an event.

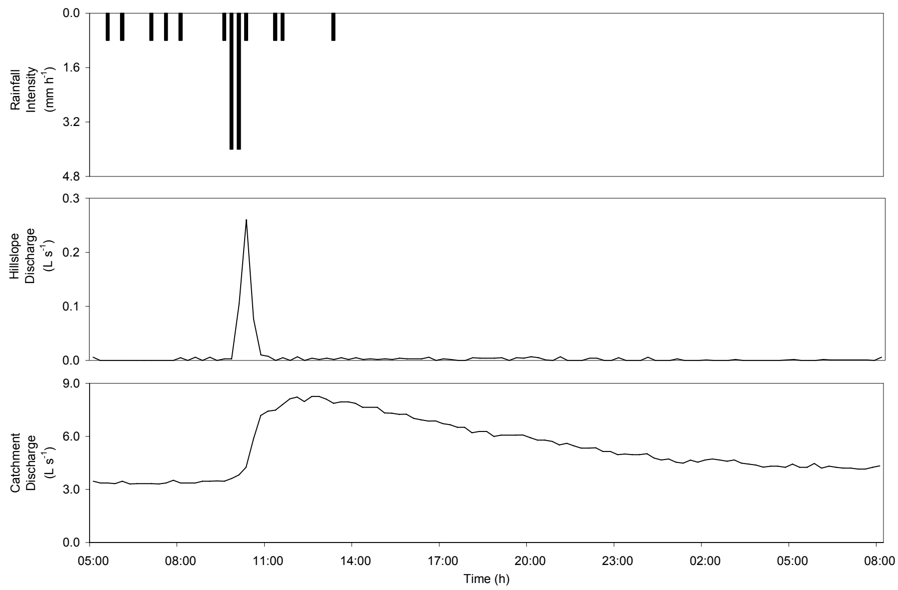

Fig. 3 Rainfall and flow data for the Longlands hillslope and Jubilee catchment, for an example event, 8 March 2006.

Table 2 Flow characteristics for P transfer events monitored in 2004–2005 and 2005–2006.

Scale of Observation	Event	Flow Peak discharge ($L\ s^{-1}$)	Discharge yield (L)	Duration (h)	Peak lag time (h)
Longlands Hillslope	I	0.1	885	7.00	1.00
	II	0.3	3 195	7.25	0.75
	III	No response			
	IV	2.6	39 982	58.00	32.00
	V	No response			
	VI	0.3	2 009	26.25	0.50
Jubilee Catchment	I	2.9	144 086	18.00	3.50
	II	7.6	245 180	34.50	1.50
	III	5.2	217 788	24.75	4.00
	IV	107.1	7 758 953	121.75	32.50
	V	2.4	304 254	65.50	1.25
	VI	8.1	1 427 616	103.25	2.00

Sediment

In three out of the four events which can be compared, the SS peak lag time was shorter at the hillslope scale than at the catchment scale, by between 1.5 and 2.5 h (Table 3). In the fourth event, however, SS peak lag time was considerably longer at the hillslope than in the stream. Figure 4 illustrates the strong relationship of SS to flow on the hillslope, and the sharper peak of the SS response compared to the flow response in the stream. In one of the seven P events monitored (event III) no SS event response was observed on the hillslope, while in event V, a small SS response was recorded despite no flow response being monitored. Concentrations of SS at the hillslope scale are considerably higher than those seen at the catchment scale, with

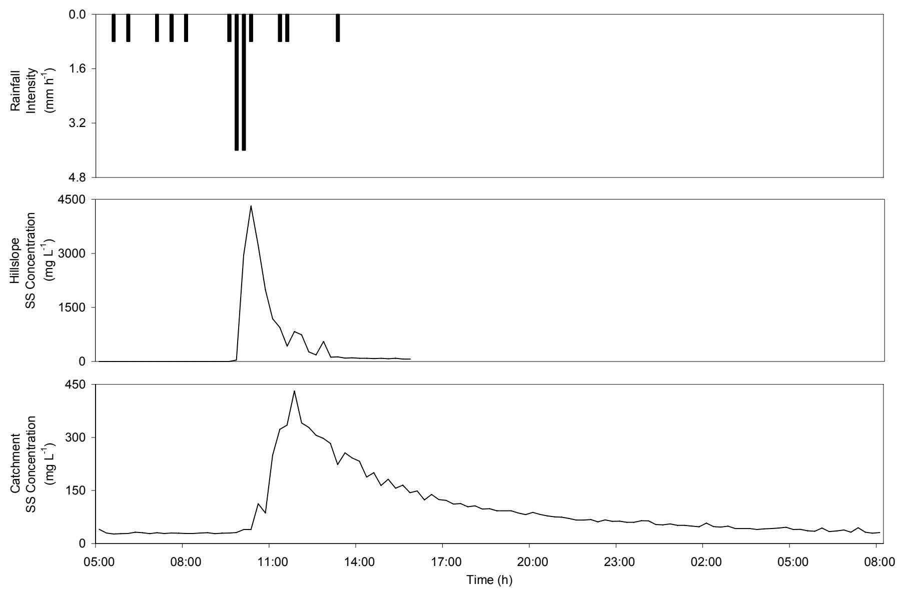

Fig. 4 Suspended sediment data for the Longlands hillslope and Jubilee catchment, for an example event, 8 March 2006.

Table 3 Sediment transfer characteristics for P transfer events monitored in 2004–2005 and 2005–2006.

Scale of observation	Event	Sediment Peak SS Conc. (mg L^{-1})	SS Yield (kg)	Peak lag time (h)
Longlands Hillslope	I	698	0.144	5.00
	II	No data		
	III	No response		
	IV	11 443	124.390	0.25
	V	393	0.002	0.75
	VI	4 316	3.339	0.50
Jubilee Catchment	I	2 360	1.088	34.75
	II	48	1.452	1.75
	III	281	14.460	1.00
	IV	255	24.846	4.25
	V	2 245	3495.856	1.75
	VI	113	12.312	3.25

peak concentrations of 11.4 mg L^{-1} recorded in the hillslope flume compared to 2.2 mg L^{-1} in the stream. High SS concentrations in hillslope flow mean that SS fluxes from the hillslope contribute a greater proportion of SS to catchment yields than is the case for flow, with the hillslope yielding up to 6.6% of catchment SS yields (event I).

Phosphorus

Peak lag times for TP for the hillslope are generally shorter than the peak lag times seen in the stream (Table 4), although the two P components, $TP_{<0.45\mu m}$ and $TP_{>0.45\mu m}$,

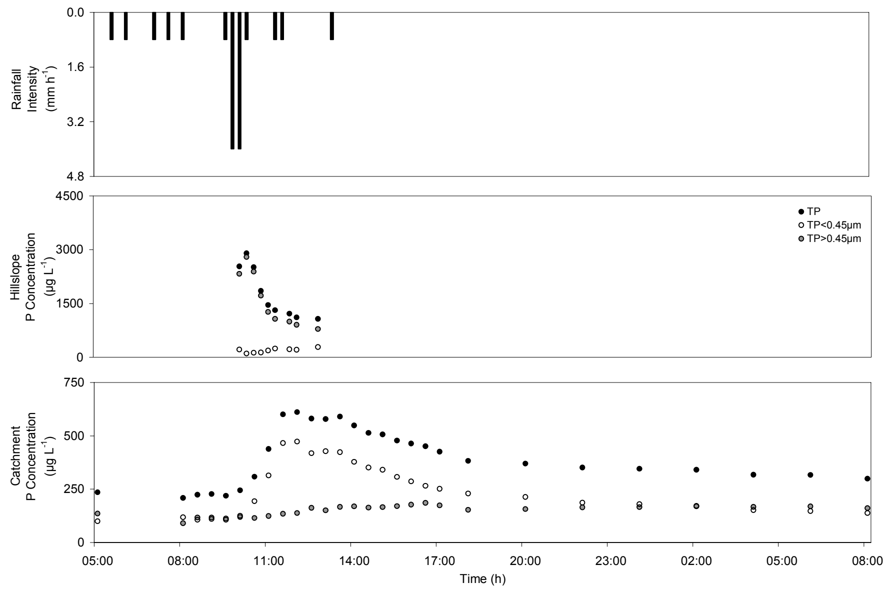

Fig. 5 Phosphorus data for the Longlands hillslope and Jubilee catchment, for an example event, 8 March 2006.

Table 4 Phosphorus transfer characteristics for events monitored in 2004–2005 and 2005–2006.

Scale of observation	Event	TP			Peak $TP_{<0.45\mu m}$			Peak $TP_{>0.45\mu m}$		
		Peak conc. (µg L^{-1})	Event yield (g)	Peak lag time (h)	Peak conc. (µg L^{-1})	Event yield (g)	Peak lag time (h)	Peak conc. (µg L^{-1})	Event yield (g)	Peak lag time (h)
Longlands Hillslope	I	886	0.3	5.25	306	0.1	3.75	644	0.2	5.25
	II	675	0.4	3.50	183	0.2	3.25	531	0.2	4.25
	III	No flow response								
	IV	4077	119.7	0.25	973	10.4	24.00	3969	109.3	0.25
	V	No flow response								
	VI	2897	19.4	0.50	381	1.8	–24.25	2793	17.6	0.50
Jubilee Catchment	I	268	12.4	8.00	229	9.7	8.00	71	2.7	1.75
	II	364	35.3	3.50	233	20.8	5.00	181	14.6	3.00
	III	1012	155.3	7.00	625	80.9	3.50	452	74.4	5.00
	IV	2443	13 029.2	1.75	1050	5634.9	21.25	1915	7394.3	2.00
	V	264	673.5	4.00	127	634.8	3.50	165	38.7	4.00
	VI	611	1 132.3	2.25	198	627.7	–14.75	473	504.6	2.25

exhibit differing behaviour. Shorter peak lag times are seen at the hillslope scale than in the stream for $TP_{<0.45\mu m}$ in events I, II and VI, but a longer peak lag time is seen in event IV. For $TP_{>0.45\mu m}$, the peak lag time is longer on the hillslope in events I and II and shorter in events IV and VI. Where negative $TP_{<0.45\mu m}$ peak lag times are seen in event VI, this reflects the response of the dissolved P fraction to the first peak of a bimodal event, while TP, PP and SS respond to the second more intense rainfall peak. As illustrated in Fig. 5, the behaviour of $TP_{>0.45\mu m}$ is often closely related to TP, with identical peak lag times for events I, IV and VI on the hillslope, and events V and VI in the stream. In the events where TP and $TP_{>0.45\mu m}$ peak lag times are different, the

$TP_{>0.45\mu m}$ lag time is longer on the hillslope, but may be either longer or shorter in the stream. Where the behaviour of TP and $TP_{>0.45\mu m}$ is different in the stream, the contribution of $TP_{>0.45\mu m}$ to TP is lower.

Both TP and $TP_{>0.45\mu m}$ concentrations are higher at the hillslope than at the catchment scale. Peak concentrations of 4.1 mg L^{-1} TP and 4.0 mg L^{-1} $TP_{<0.45\mu m}$ were measured in the hillslope flume, compared to concentrations of 2.4 mg L^{-1} and 1.9 mg L^{-1} in the stream. This is also the case for $TP_{<0.45\mu m}$, although in one event (event II), $TP_{<0.45\mu m}$ concentrations were slightly higher in the stream. Peak $TP_{<0.45\mu m}$ concentrations are lower than $TP_{>0.45\mu m}$ concentrations, with peak values of 1.0 mg L^{-1} $TP_{<0.45\mu m}$ measured at both the hillslope and catchment scales. In half the events in the stream, peak $TP_{<0.45\mu m}$ concentrations are higher than $TP_{<0.45\mu m}$ concentrations, with $TP_{<0.45\mu m}$ being relatively more important at the catchment scale than at the hillslope scale. Yields of TP from the hillslope are between 0.9% (event IV) and 2.5% of catchment TP yield, while for $TP_{<0.45\mu m}$, the values are between 0.2% (event IV) and 1%. The hillslope yields a greater proportion of the catchment particulate P, with the maximum hillslope $TP_{>0.45\mu m}$ contribution to catchment yield being 7.4%. The maximum contributions hillslope P to the catchment outlet all occur in event I.

DISCUSSION

The main purpose of this research was to increase P process understanding in an agricultural context, through exploration of hydrological, sediment and P transfer characteristics and relationships at different scales of observation within a first-order catchment. The results presented here have shown that there are differences in responses between the hillslope scale and the catchment scale for flow, sediment, and P fractions, and between events for each scale of observation, suggesting that the dynamics of both SS and P transfer are complex.

Flow on the hillslope is particularly flashy, and as there is no baseflow component at this scale, flow responses to rainfall directly influence the nature of both SS and P transfer. As an SS response was seen at the hillslope scale in an event where no corresponding flow response occurred, very small volumes of flow (below the detection level for monitoring) are able to generate a noticeable SS response, which is not unexpected as the transfer system is initially transport limited at this scale. Flow at the hillslope scale is generally short-lived, which may explain why the yields are low in comparison to those seen at the catchment outlet. The greatest proportion of SS to catchment SS yields from the hillslope occurs when the SS and P peak lag times are longest; suggesting that the transport of SS and P during events may generally become source limited after the initial sediment supply is moved off the hillslope. High concentrations of both SS and P in hillslope flow mean that this scale of observation becomes important as a source of sediment and nutrient transfer when SS and P are considered, although it appears to be a minor source when considered at the catchment scale. Although not discussed here, drainflow sources, in combination with in-stream sediment cycling (Jarvie *et al*., 2005), are therefore likely to be the dominant processes involved in SS and P delivery to the catchment outlet.

CONCLUSIONS

Gaining a better understanding of the processes and linkages operating in agricultural catchments is essential in order to understand how diffuse sources of pollution influence the water quality of fluvial systems. One of the key limitations is a lack of available data at a range of spatial scales, which is necessary to improve process understanding and model development. The results presented here indicate the differing behaviour of both sediment and P over six events, throughout two hydrological years, between two scales of observation, the hillslope and the first-order catchment. The transfer of sediment and P at both scales of observation appears to be complex. High SS and P concentrations in hillslope flow mean that the hillslope does represent a significant source of SS and P delivered to the catchment outlet, although other processes operating within the catchment are likely to be more important, such as the transfer of fine sediments and P through drainage systems, and the recycling of sediment and P from channel bed sources.

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