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PRIMARY RESEARCH PAPER

Monitoring the fluvial palynomorph load in a lowland temperate catchment and its relationship to suspended sediment and discharge

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Abstract Despite it being a component of the seston we know very little about fluvial (waterborne) pollen and spore (palynomorph) transport. This paper presents the results of a monitoring programme conducted over two years and at a catchment scale in South West England. A hierarchical monitoring network was established with flood peak samples taken at 9 sub-catchments, intra-hydrograph samples taken in two sub-catchments and time-integrated sampling undertaken at one location. In addition sampling was undertaken of probable palynomorph sources such as channel bed and bank sediments, and the airborne pollen flux was monitored using modified Tauber traps. The results support previous research in illustrating how the vast majority of fluvial pollen and spores are transported during floods (91%) and that the main control on waterborne palynomorph assemblages is the catchment vegetation and its spatial distribution but with a long-distance (extra-catchment) component. However, strong seasonal effects are also shown, and the importance of distinctive sources such as the riparian input, bed re-suspension and overland flow into drains and tributaries is revealed. Fine sediment in river pools appears to act as a selective store of damaged cereal type pollen grains derived from arable fields. Although pollen does form part of composite particles the data presented here suggest that the majority of the pollen is transported as single grains. Fluvial palynomorph loading is strongly dependant upon discharge and so concentrations in laminated or varved sediments could be regarded as a proxy for flood magnitude.

Keywords Seston · Fine particulate organic matter · Waterborne pollen · Suspended sediment · organic transport

Introduction

Pollen and spores, here collectively referred to as palynomorphs, are a persistent component of river seston or fine particulate organic matter (FPOM) and part of the flux linking upstream and downstream reaches of river ecosystems. Artificially introduced

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pollen has also been used as a seston analogue (Miller & Georgian, 1992) without much knowledge of the transport characteristics of palynomorphs. Rivers are also the major source of palynomorphs input into most lakes and near-shore marine sediments (Federove, 1952; Peck, 1973; McAndrews & Power, 1973; Crowder & Cuddy, 1973; Pennington, 1979; Bonny, 1980; Brown, 1985; Fall, 1987; David & Roberts, 1990; Traverse, 1992, 1994), but are far less well understood than the airborne component. The aim of the monitoring project reported here was to understand the relationship of palynomorph transport to river discharge, their relationship to the transport and deposition of suspended sediment and thereby investigate their possible use as natural sediment tracers.

Studies of fluvial pollen and spore transport are rare but have revealed that flood concentrations can be from 100,000 g ml^{-1} (Peck, 1974) to as high as 130,000–230,000 g ml^{-1} (Brown, 1985). Pollen and spores transport has also been investigated in flumes (Brush & Brush, 1972), and Holmes (1990) reported no differential sorting at velocities over 0.30 m^{-1} s^{-1} (Holmes, 1990; 1994). Meade et al. (1990) also report that flood-borne pollen is well mixed. It is widely accepted that the majority of pollen and spores entering small lakes and ponds are derived from headwaters along with the rest of the seston, and that the ratio of fluvial to airborne input depends on the size of the catchment, the lake surface area, the topography and the catchment vegetation. In classic studies Peck (1973, 1974) found 97% of the pollen and spore input to Oakdale reservoir was fluvial, and Bonny (1978) found 87% of the input to Blelham Tarn was of fluvial origin. However, little is known of the seasonal variation in this component of the seston, its transport and its storage within the stream system.

We can define the fluvial palynomorph flux (F_l) as being the combination of several distinct components:

$$F_l = Q(A_c + R_c + O_c + B_c + \Delta S_c) \qquad (1)$$

where Q is the stream discharge in m^3 s^{-1} and A_c is the direct airborne component which includes the extra local and regional component (*sensu* Jacobsen & Bradshaw, 1981) and which is proportional to channel area, R_c is the riparian local component, O_c is the direct overland flow component, B_c is the bank erosion component and S_c is river storage in bed sediments which can be re-suspended during floods (all in grains l^{-1}). Using the analogy with forest gaps and lakes (Jacobsen & Bradshaw, 1981) for rivers less than 30 m wide the significant terms can be reduced to R_c, O_c and S_c. This is because at this scale A_c would be proportionately minor due to a very small unimpeded direct fall area. However, it is this fraction (A_c) that has been modelled to produce quantitative estimates of vegetation cover (Prentice & Parsons, 1983; Prentice, 1985, 1986, 1988; Sugita et al. 1999). It can also be assumed that the bank erosion (B_c) component would be quantitatively small due to the low concentrations of pollen in clastic sediments and the non-organic-rich horizons of soils (Brown, 1985), although it might be important in the composition of the palynomorph assemblage. However, there is little data on the relative input of these components and the sampling strategy employed in this study was designed to allow some quantification of these different input sources.

Study site and methods

The site chosen for this study was the Exe Basin in SW England (Fig. 1). The River Exe drains an area of 1,530 km^2; its source rises at Exe Head on Dure Down, Exmoor (SS 752 415) and flows 87.2 km west and south until it reaches the Exe Estuary at Exmouth. The Exe catchment was chosen for this study as it exhibits considerable diversity with regards to vegetation cover, hydrological regimes and climatic conditions (Walling & Moorehead, 1987). Thirteen sub-catchments were monitored (data from 9 is used here) to sample this variety. Within the Exe catchment there is an established hydrometric monitoring network operated by the University of Exeter and the Environment Agency, providing suitable monitoring data along with the availability of meteorological data supplied by the British Atmospheric Data Centre. Finally, the Exe catchment has been extensively studied and there is subsequently a large amount of literature relating to catchment sediment dynamics (for example Walling & Webb, 1981; Walling & Woodward, 1993; Walling et al., 1993; Walling & He, 1994; Nicholas & Walling, 1995; Collins et al., 1997a, b; Blake et al., 2002; Collins & Walling, 2002). The geology of the catchment is dominated by Devonian sandstones, slates and conglomerates in the north, and

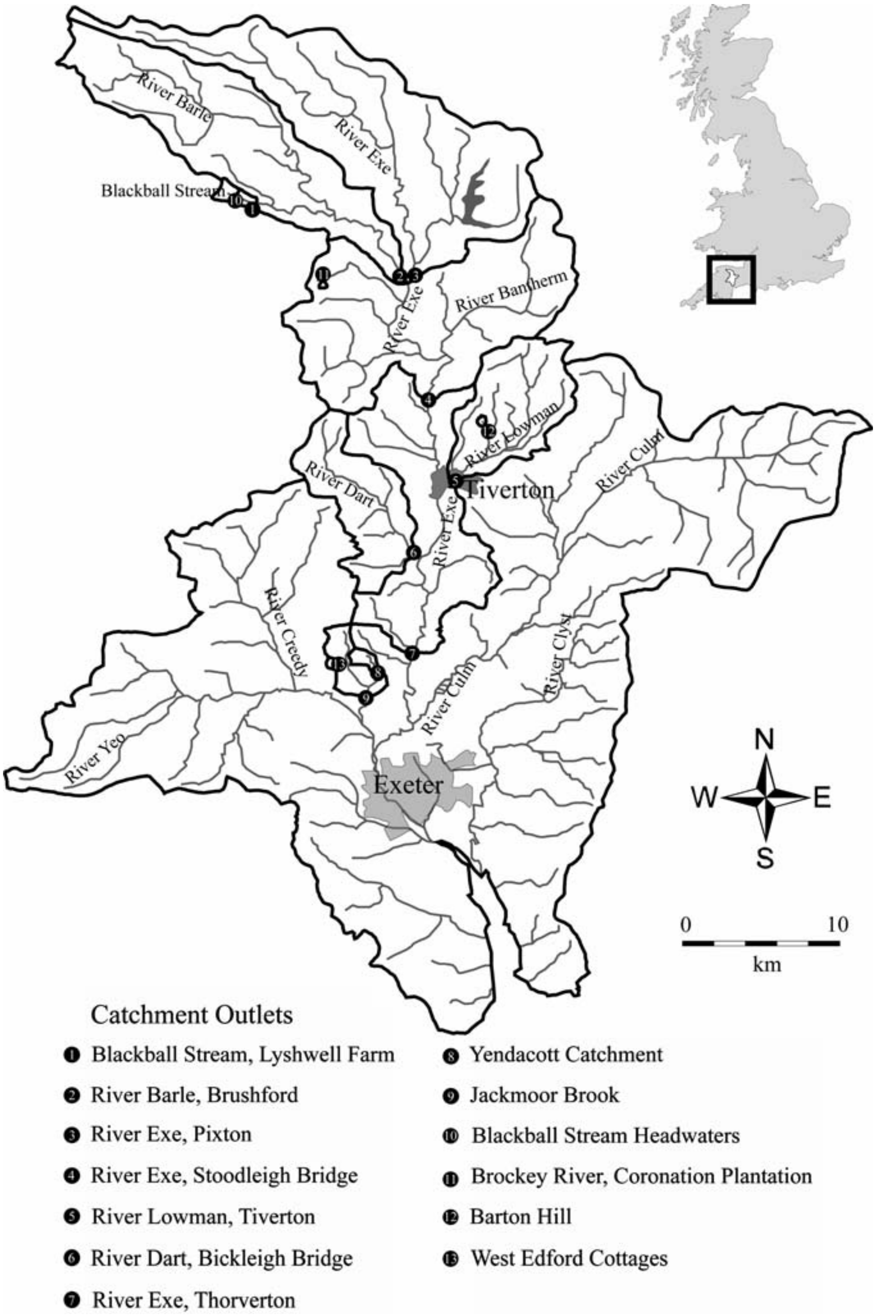


Fig. 1 The location of the Exe basin and the sub-catchments monitored as part of this study

Carboniferous sandstones, conglomerates and mudstones in the middle and south with one area of Cretaceous Upper greensand in the east. The catchment lay outside the maximum Pleistocene glacial limits and has a well-developed strath terrace staircase and basin and gorge type floodplain. The relative relief of the catchment is 519 m and slopes are steepest in the headwaters. The average slope angle is 17° (Webb, 1980), but with considerable variation in the sub-catchments (Table 1). The catchment has a mean annual precipitation of 1,097 mm but this also varies in the sub-catchments from 900–3262 mm yr^{-1}. The mean daily flow at Thorverton is 9 $\text{m}^3\ \text{s}^{-1}$ with 0.01 probability of exceedance flow being 90 $\text{m}^3\ \text{s}^{-1}$ and the 0.99 probability being 1.4 $\text{m}^3\ \text{s}^{-1}$.

Table 1 Topographic statistics for the study catchments taken from the Flood Estimation Handbook CD-ROM (Centre for Ecology and Hydrology, 2002)

Catchment		Area (km^2)	Max. drainage Path (km)	Mean slope (m/km)	Mean aspect (°)	Catchment outlet altitude (m O.D.)	Mean altitude (m O.D.)	Max. altitude (m O.D.)
1	Lyshwell Farm	1.8	2.88	66.9	93	287	345	378
2	Brushford	128.8	40.99	136.4	152	128	245	488
3	Pixton	149.8	36.79	153.8	185	128	307	519
4	Stoodleigh	420.7	55.44	142.5	168	74	284	519
5	Tiverton	54.5	15.87	95.1	192	62	168	286
6	Bickleigh	45.4	14.33	146.2	132	52	176	271
7	Thorverton	608.9	76.92	137.8	164	26	244	519
8	Yendacott	1.5	2.38	48.9	161	35	59	85
9	Pyne cottage	9.3	5.48	58	158	25	66	235

Vegetation cover and land use was extracted from the Land Cover Map of Great Britain (1990) produced from Landsat Thematic Data (Fuller et al., 1994). This allowed the land use in each of the sub-catchments to be quantified. Four types of catchment were identified, predominantly pasture and heathland (sub-catchments 1–3), predominantly pasture and deciduous woodland (sub-catchments 4, 6), predominantly pasture and arable (catchments 5,7) and predominantly arable cultivation (catchments 8,9).

Peak flow samples were taken from the outlet of each of the sub-catchments during floods over a period of 24 months. In addition, background low-flow samples were collected, and at two stations samples were taken through storm events (hydrograph samples). Samples were taken either using a submersible pump and portable generator or by hand from the middle of the river at an approximate height of 0.6× the maximum river depth. This was done in order to ensure that the water was fully mixed and avoided the problem of surface water assemblages being biased towards more buoyant and unsaturated pollen grains (Hopkins, 1950; Traverse and Ginsburg, 1966; Traverse, 1988). This assumption was also tested by sampling a depth profile at an intermediate flow (see results). The volume of water samples was varied depending upon the suspended sediment concentration from as much as 10 l at sites with low concentrations (e.g. catchment 1, Lyshwell Farm) to only 2 l (Catchment 9, Pyne Cottage). This was estimated from standard 10-l samples taken during the first two floods.

In addition samples were taken of the bed sediment in a pool and riffle using a 1-m-high steel cylinder pushed into the bed and the water agitated before sampling (Lambert and Walling, 1988). This sediment re-suspension technique was adopted to sample the pollen which could be re-suspended during a flood event. Eight samples were also taken from an actively eroding river bank in the Bickleigh reach of the River Dart (sub-catchment 6) which is both typical of the catchment and central. All the water samples were filtered (some after centrifugation at 2500 rpm for 10 minutes as per standard palynomorph processing (Moore et al., 1991)) using glass fibre Whatman filters (GF/A) with a pore size of 1.6 µm. The filters were than oven dried and the suspended sediment weight recorded before they were subjected to a standard chemical processing using hydrofluoric acid digestion followed by acetolysis. Pollen concentrations were determined by the addition of *Lycopodium clavatum* tablets containing a known number of spores (Stockmarr, 1971). Pollen identification routinely used 500× magnification with 1000× magnification for small and difficult types with reference to standard keys (Andrew, 1984; Faegri and Iversen, 1989; Moore et al., 1991) and the Exeter University Pollen and Spore reference collection. Pollen and spore nomenclature follows Bennett et al. (1994). Pollen preservation was recorded using a threefold classification adapted from Delcourt and Delcourt (1980); corroded, degraded and mechanically damaged. Where more then one form of degradation was present only the most developed was recorded.

At each of the sub-catchment sampling stations airborne pollen flux was also monitored using a modified Tauber trap (Tauber, 1974; Hicks and Hyvaarinen, 1986) with a central aperture of 5-cm diameter and sloping collar of 15-cm diameter. The traps were located in an open area of at least 30-m diameter. The traps were not meshed and the samples were processed in the same way as the water and bank samples with hydrofluoric acid digestion followed by acetolysis.

To be able to compare the pollen data with the land use data and identify sources it was necessary to convert the pollen and spore data into 8 vegetation/land use classes (Table 2). This is inevitably imperfect due to problems of taxonomic precision, but was done using the ecology of the majority species in each of the pollen types *sensu* Bennett (1994). There are clearly some species of a different ecology within these groups, but the overwhelming majority in pollen producing terms will have been derived from that vegetation type (e.g. *Ranunculus* includes aquatic species but the vast majority of pollen will be from pasture species). The procedure is described in more detail in Brown et al. (2007) which also related the palynomorph-derived vegetation classes to the subcatchment land use as determined using the Landsat Thematic Data.

Results

Pollen and spore hydrographs

Sampling of the vertical water profile (Fig. 2) showed the pollen and spores to be well mixed, but with a distinctly higher concentration (50%–20%) at the water surface. This has been observed before (see discussion) and validates the unbiased nature of samples taken from a single depth.

Sampling through floods at Bickleigh and Thorverton illustrates the dramatic increase in pollen and spore concentration through the flood hydrograph with peak concentrations at Bickleigh reaching 7,000 grains l^{-1} even on January 23rd 2001 (Fig. 3) and coincident with the peak in discharge and suspended sediment. At Thorverton peak concentration is even higher for the same event reaching 35,000 grains l^{-1} coincident with the peak in suspended sediment but preceding the peak discharge (Fig. 3). Damaged grains show a similar trend, but with the second highest concentration being that of arable types which at Thorverton is lagged behind the other types. These concentrations are too high at 3,700 and 18,000 grains l^{-1}, respectively, to simply be derived from the channel bed and banks which never exceed 5,000 grains l^{-1} in total (Fig. 5 and later

Table 2 Simplified land cover and associated pollen taxa

Simplified land cover class	Associated pollen taxa
Disturbed ground	*Papaver rhoeas*-type, Chenopodiaceae, *Urtica*-type, Hypericum perforatum-type, Brassicaceae, Apiaceae, Lamiaceae undiff., *Mentha*-type, *Scrophularia*-type, *Rhinanthus*, *Valeriana officinalis*, *Arctium*-type, *Artemisia*-type.
Pasture	*Ranunculus*, Caryophyllaceae, *Polygonum*, *Rumex acetosella*, *Rumex acetosa*, *Umbilicus rupestris*-type, *Potentilla*-type, *Astragalus danicus*-type, *Lotus*, *Medicago sativa*, *Trifolium*-type, *Gentianella campestris*-type, *Plantago lanceolata*, *Digitalis purpurea*-type, *Scabiosa columbaria*, *Cirsium*-type, *Centaurea nigra*, Lactuceae, S*olidago virgaurea*-type, *Aster*-type, Poaceae undiff.
Marsh	*Sphagnum*, *Caltha palustris*-type, *Persicaria bistorta*-type, *Montia fontana*, *Filipendula*, *Gentiana*-type, *Valeriana dioica*, *Succisa pretensis*, Cyperaceae undiff.
Heath/moorland	*Lycopodium*, *Juniperus communis*, *Betula*, *Vaccinium*-type, *Calluna vulgaris*, *Ulex*-type.
Bracken	*Pteridium aquilinum*.
Deciduous woodland	Pteropsida monolete undiff., *Polypodium*, *Dryopteris*-type, *Ulmus*, *Juglans regia*, *Fagus sylvatica*, *Quercus*, *Alnus glutinosa*, *Corylus avellana*-type, *Tilia cordata*, *Populus*, *Salix*, *Rhododendron ponticum*, *Ribes*, *Rubus*, *Rosa*, *Sorbus*-type, *Ilex aquifolium*, *Acer campestre*, *Hedera helix*, *Fraxinus excelsior*, *Sambucus*.
Coniferous woodland	*Abies*, *Picea*, *Pinus sylvestris*.
Arable	*Avena*-type, *Hordeum*-type, *Secale cereale*, *Zea mays*.

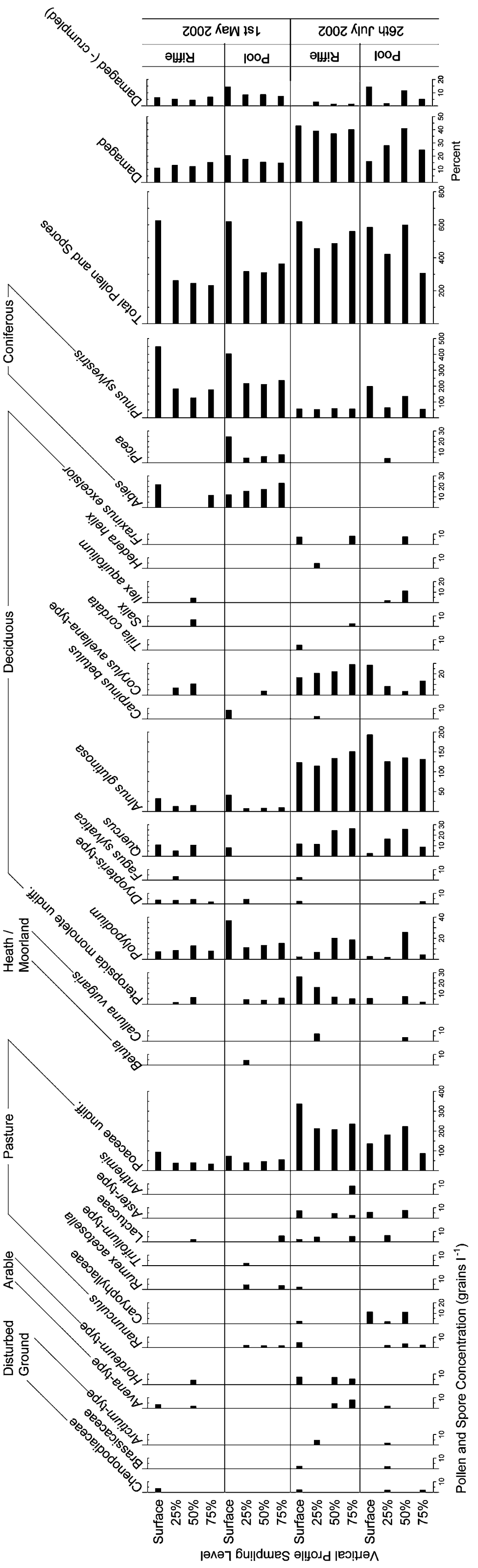


Fig. 2 Vertical depth profiles of pollen and spore concentrations sampled from the River dart at Bickleigh (sub-catchment 6)

discussion). Integrating over the entire storms these concentrations would require unrealistically large areas of bank erosion to be the main source. Therefore these concentrations must reflect pollen being washed in from other sources such as overland flow into tributaries and drains as well as some riparian wash-off. Unsurprisingly spring hydrographs show even higher concentrations reaching 150,000 grains l^{-1} at Bickleigh, but only 7,000 grains l^{-1} at Thorverton (Fig. 3) probably due to the location of the storm over the Dart Catchment. Arable types are again disproportionately high in relation to the percentage of area covered by arable fields in both catchments (Brown et al., 2007). In April peak concentrations reach 22,000 grains l^{-1} with damaged arable types alone reaching 11,000 grains l^{-1} (Fig. 3). Autumn hydrographs (Fig. 3) show a fall in peak concentrations to 7,000 and 50,000 grains l^{-1} and arable types, both undamaged and damaged, become proportionately less important, whilst arboreal types become more important.

The relatively high proportion of damaged grains, and particularly those of the arable group is echoed in the river bed samples (Fig. 4). These show that in the Dart sub-catchment, which is predominantly pasture and woodland, *Avena* type is the second highest concentration after Poaceae reaching over 1,500 grains g^{-1} of sediment. Typical rates of suspended sediment concentration of 0.2–2 g l^{-1} could produce re-suspended *Avena* concentrations of 300–3,000 g l^{-1} in the absence of exhaustion effects. Nearly all these grains which must have been derived from arable fields were broken, crumpled or degraded providing a potential signature of this pollen component (S$_c$). This is an important potential store of pollen and is probably the source for much of the degraded pollen (Fig. 3), particularly the arable pollen, observed in the flood samples.

Bank-erosion-derived input

The bank sediment component represents the long-term palynomorph store from local vegetation and overbank sedimentation. Due to oxidation-reduction cycles the average proportion of damaged grains (excluding crumpled grains) is higher than the fluvial and bed storage component at 32% (Fig. 5). The concentrations of the bank samples ranged from 6,300 to 9,300 grains g^{-1} (mean 7,400 grains g^{-1})

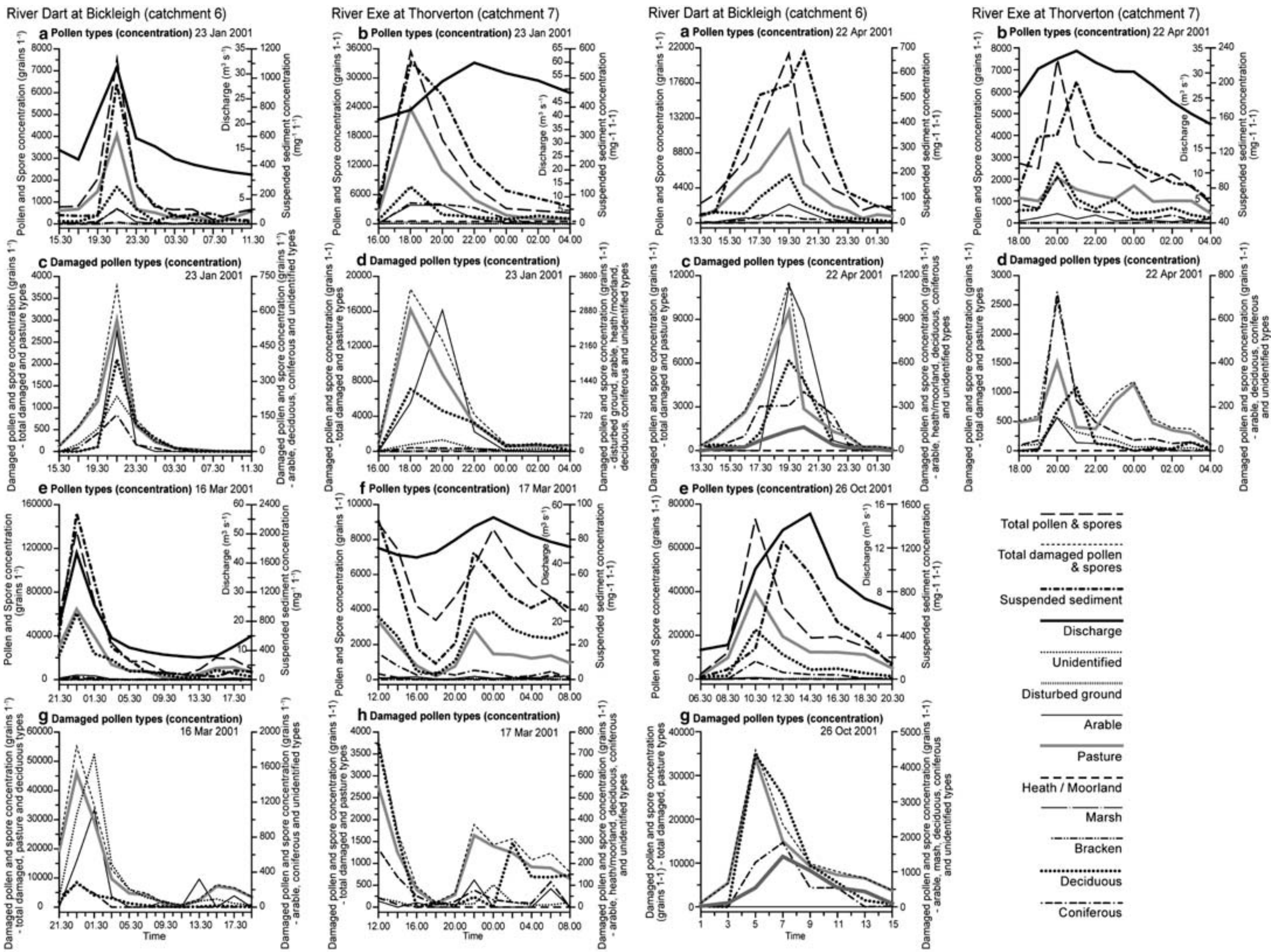


Fig. 3 (**a**) Discharge, suspended sediment and pollen and spore concentration (**b**). damaged pollen and spore concentration, sampled from the River Dart at Bickleigh (catchment 6) commencing 15.30, 23rd January 2001, the River Exe at Thorverton (catchment 7) commencing 16.00, 23rd January 2001, the River Dart at Bickleigh (catchment 6) commencing 21.30, 16th March 2001 and the River Exe at Thorverton (catchment 7) commencing 12.00, 17th March 2001

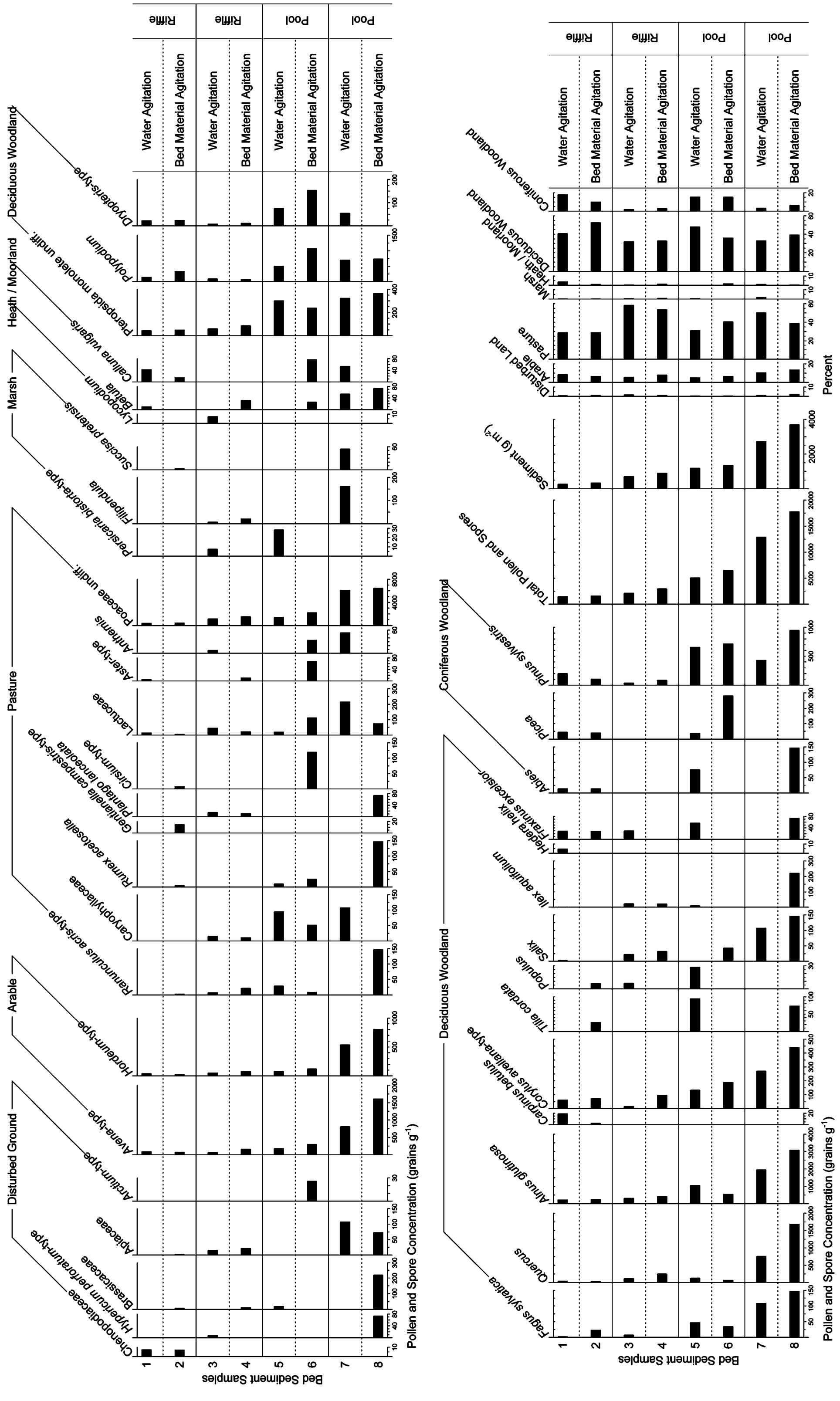


Fig. 4 River bed pollen storage-damaged grains (grains g^{-1}) sampled from the River Dart at Bickleigh (sub-catchment 6)

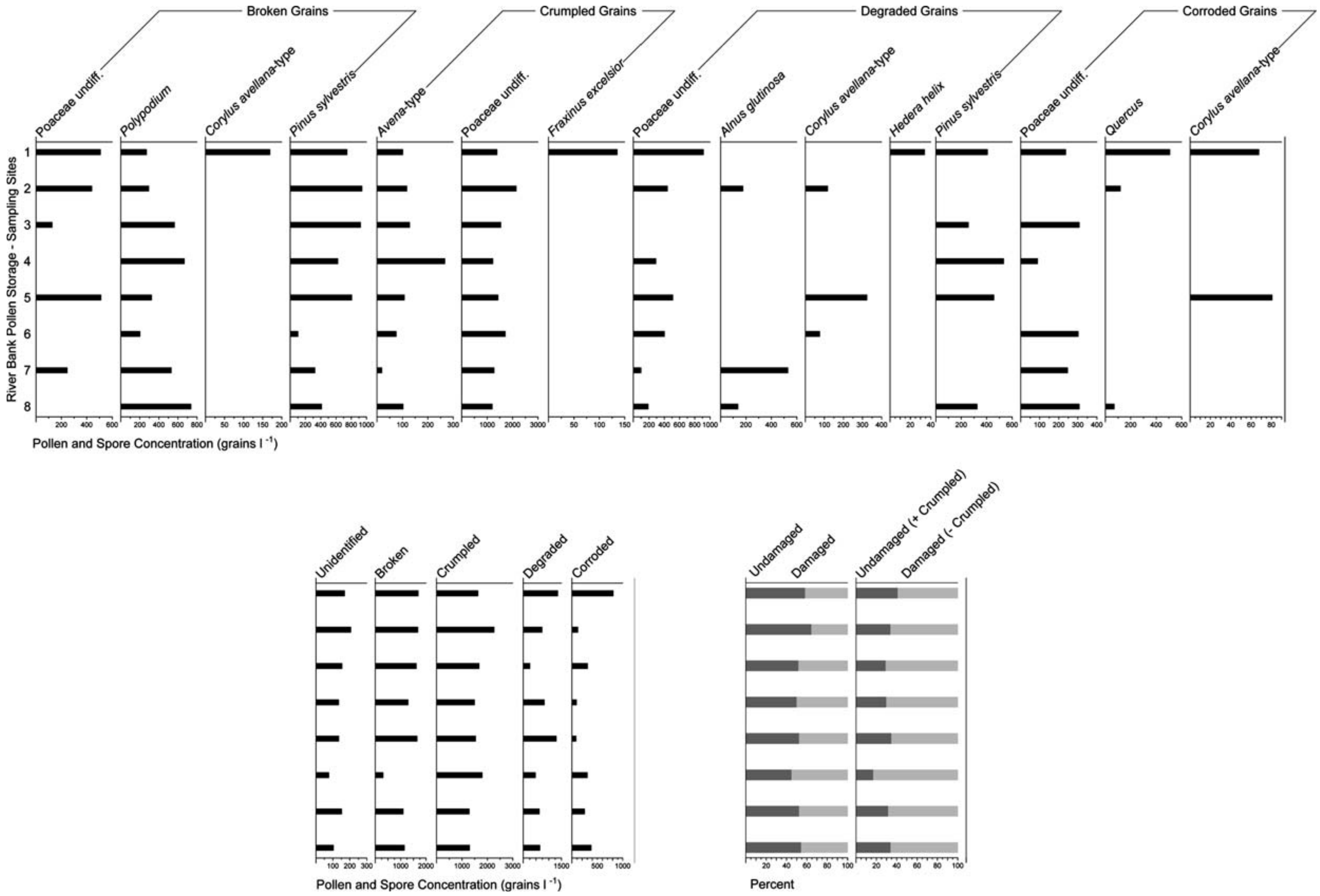


Fig. 5 River bank samples showing damaged pollen concentrations sampled from the River Dart at Bickleigh

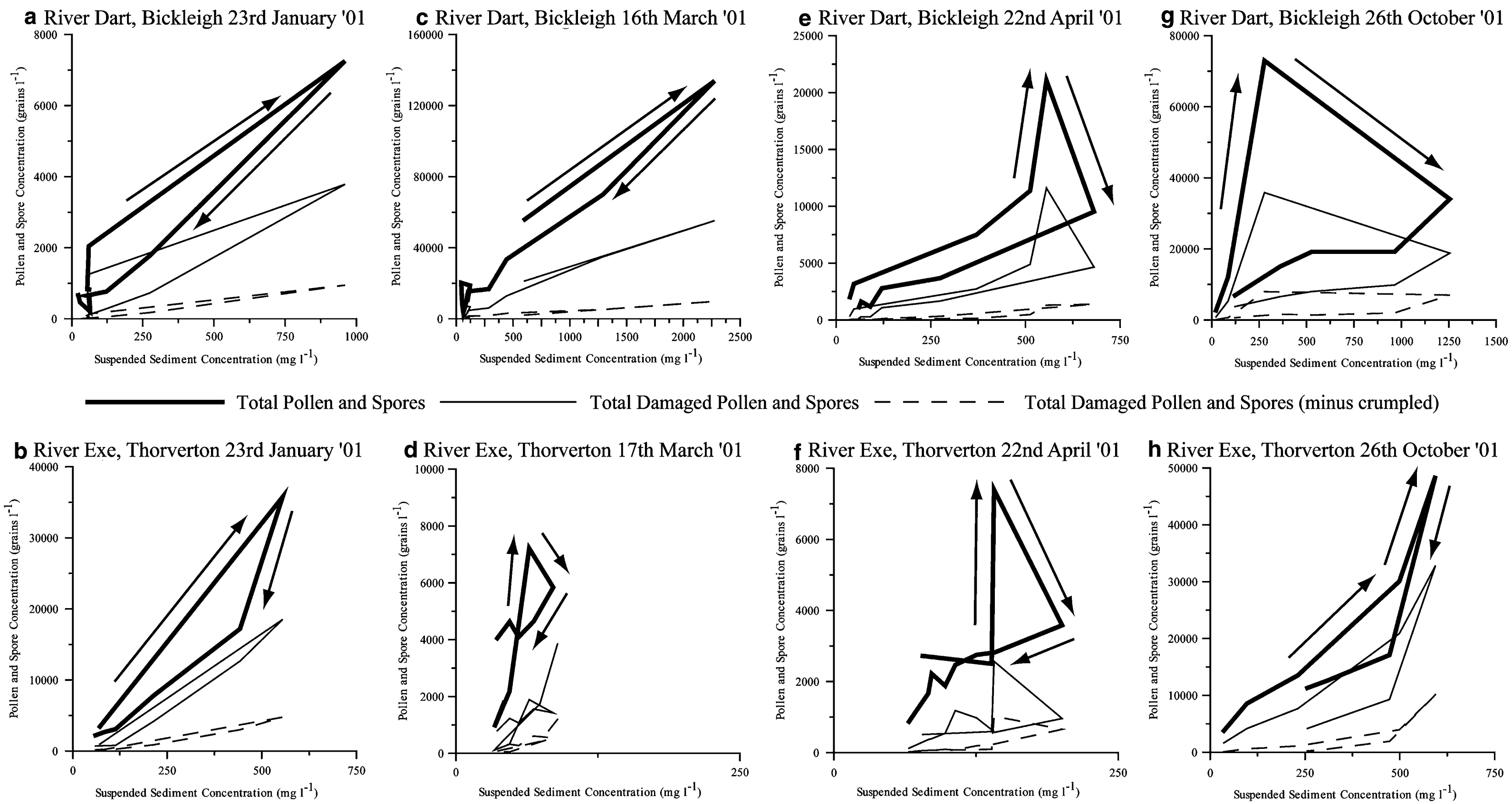


Fig. 6 Total pollen and spore concentrations and suspended sediment relationships storm by storm

and are similar to the river bar (7,300 grains g^{-1}) and the channel bed (6,300 grains g^{-1}) with type diversity also being comparable (37, 40, 38 per 500 pollen grain sum).

Discussion

The well mixed vertical profile of pollen types but with a higher pollen and spore concentration at the surface has also been reported by Traverse & Ginsburg (1966) and Traverse (1988) who regarded it as a function of the saturation time of airborne inputs. Starling and Crowder (1981) also observed significantly higher concentrations of pollen towards the surface of the Salmon River; a phenomenon also reported by Smirnov et al. (1996) for the Mississippi River who observed a high degree of variation within the vertical profile (600–2,300 grains l^{-1}) with the highest concentrations of two common types, *Pinus* and *Salix*, occurring at the surface. Smirnov et al. (1996) suggest that this high surface concentration is due to input from riparian vegetation. However, as Brush & Brush (1972) have already shown once saturated transport is mixed and unsorted by size or type.

The flood sampling shows that hysteresis plots exhibit variation both site to site and during the year (Fig. 6). Both the March and October loops for Bickleigh show a rapid increase and decrease in discharge and palynomorph concentration, whereas the January plot shows under-sensitivity (Brown & Quine, 1999) in the palynomorph availability. However, the January plot at Thorverton displays hypersensitivity reaching 35,000 g l^{-1} with only 600 mg l^{-1} of suspended sediment followed by exhaustion before the peak discharge has been reached, whereas the March and April loops display a suppressed response. In general the relationship is characterised by clockwise loops (*sensu* Williams 1989) but counter-clockwise loops do occur especially in the late autumn and early winter due to supply limitation in the non-flowering season.

The bank sediment concentrations are far lower than the airborne influx rate as reported in Brown et al. (2007) which reached as high as 11,400 grains cm^{-2} yr^{-1} at Bickleigh (Carpenter, 2005) and the peak flow suspended concentrations presented here. This suggests that the bank erosion contribution is of far lesser quantitative importance at even peak suspended sediment concentrations than the airborne (direct and indirect), riparian and surface wash component. The degraded component of the river bed samples may, however, be preferentially derived from the bank store due to the higher proportion of damaged and degraded grains.

Palynomorph sediment relationships

As has been shown by the hydrographs (Fig. 3) the peak in palynomorph concentration is often out of phase with the peak in suspended sediment concentration. Plotting palynomorph concentration against suspended sediment concentration provides a variety of hysteresis plots as discussed earlier (Fig. 6). This suggests that much of the palynomorph load is being transported independent of the clastic sediment load. Inverted microscopic examination of flood water samples reveals palynomorph grains transported both as individual grains and as part of composite particles (Fig. 7). Although at the scale of the individual hydrograph there is a strong dependence of palynomorph concentration and discharge overall the relationship is variable as illustrated by the aggregate data from Thorverton (Fig. 8) which although statistically significant shows several data values where the palynomorph concentration greatly exceeds the expected values based upon the general trend. The cause of both this variation and the variable relationship to suspended sediment concentration is the variation in the atmospheric input during the year (Fig. 9). Although it is not possible to use traditional in situ techniques to estimate a palynomorph budget

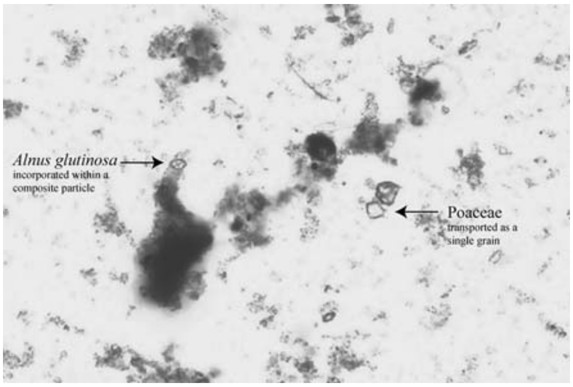


Fig. 7 Pollen grains as both composite particles and as single grains from the River Dart at Bickleigh (catchment 6) 25th July 2003 at peak flow. Picture courtesy of N. Williams

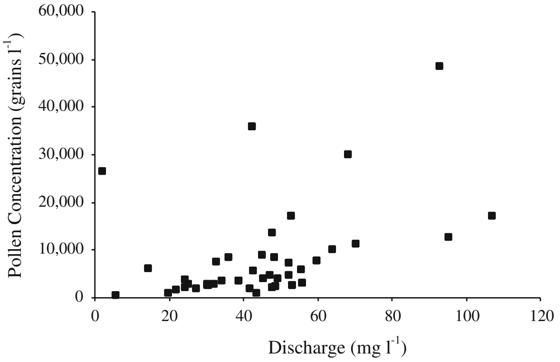


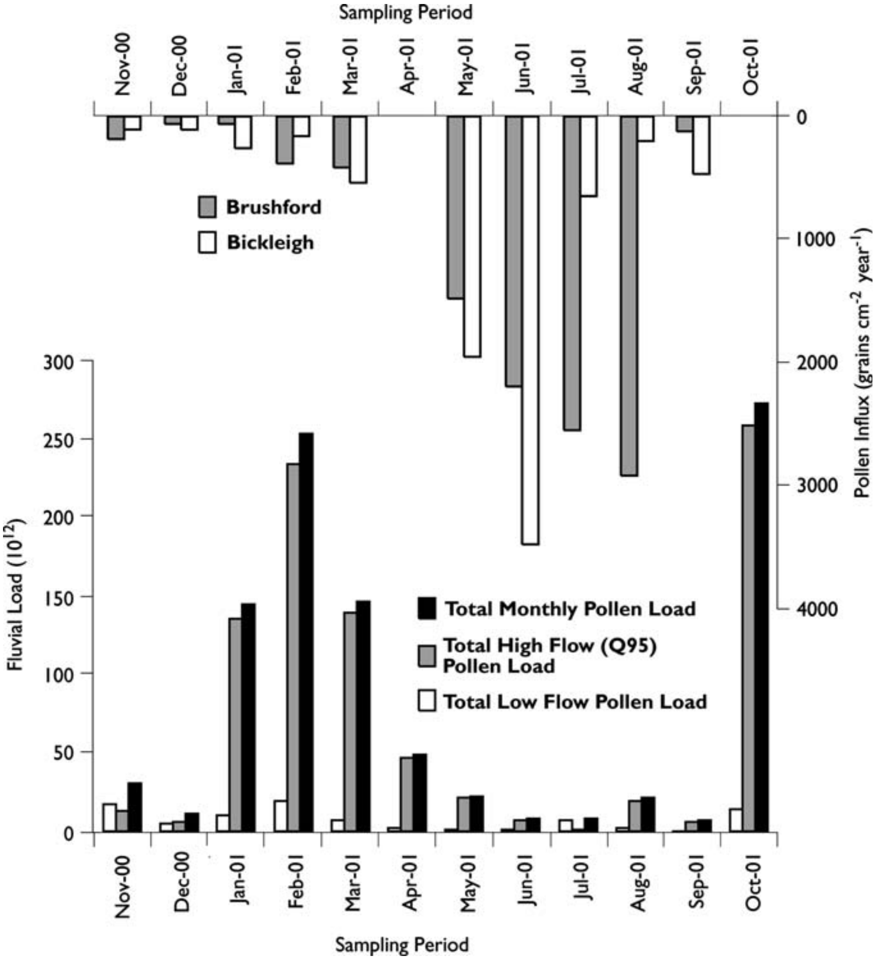
Fig. 8 Plot of discharge against suspended pollen and spore concentration, River Exe, Thorverton

an estimate can be made for Thorverton based upon the average low-flow (Q95) and high-flow concentrations for individual months (Fig. 9). This illustrates the dominance by high flows whereby 91% of the palynomorph load was transported in 5% of the year (yearly total). These calculations suggest that approximately 976 × 10^{12} grains were transported out of the Exe catchment between November 2000 and October 2001. Using an average palynomorph size of an equivalent spherical body of 60 μm this is only a small proportion of the total suspended sediment at approximately 50 g over the year.

Conclusions

This large-scale monitoring of fluvially transport palynomorphs has confirmed a number of previous conclusions derived from the limited monitoring of single sites and occasional observations. Firstly that the palynomorph water depth profile is generally uniform indicating full mixing, except for a surface

Fig. 9 Monthly pollen loading for the River Exe catchment at Thorverton based on 15min Q data and 95% duration division and the monthly airborne influx as recorded at Brushford (outlet of catchment 2) and Bickleigh (outlet of catchment 6)



enhancement effect. Secondly that the vast majority of fluvial input in this temperate mixed-land use basin occurs during flood events (91%) and thirdly that the overall variation of fluvial input is controlled by the combination of seasonality and the spatial variation in sub-catchment vegetation.

In addition, this study also shows that the strong seasonal effects cause both over and under-representation of catchment vegetation in the fluvial output. These reflect the pathways of palynomorph transport into rivers particularly direct input probably via leaf-drip of riparian vegetation, overland flow in autumn and winter, and bed sediment re-suspension. A particularly important finding is the high storage in river pool sediments of arable pollen grains, a high proportion of which are damaged but still recognisable. The exact cause of this is unknown, but it may be due to the greater settling velocity of these large grains on the declining limb of winter and spring hydrographs in areas where there are high levels of arable cultivation upstream of the sampling location. Although direct observations of the seston show that pollen can form part of composite sediment particles the data presented here suggest that the majority of the pollen and spore load is transported as single grains and forms a minor component quantitatively of the seston flux. Fluvial palynomorph loading is strongly dependant upon discharge and so concentrations in laminated or varved sediments could be regarded as a proxy for flood magnitude.

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