R&D Project 122

Effects of Agricultural Soil Erosion on Watercourses

Institute of Hydrology
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G J L Leeks

Research Contractor:
Institute of Hydrology, Plynlimon

National Rivers Authority
Rivers House
Waterside Drive
Aztec West
Bristol
BS12 4UD

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Commissioning Organisation
National Rivers Authority
Rivers House
Waterside Drive
Aztec West Tel (01454) 624400
Bristol BS12 4UD Fax (01454) 624409

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Statement of Use

This provides guidance for NRA Water Quality Officers on the likley causes and effects of agricultural soil erosion on river water quality. It represents the first phase of of project and will feed into another R&D project on to assess the of opportunities for soil erosion control.

Research Contractor
This document was produced under R&D Project 122 by:

Institute of Hydrology
Plynlimon
Staylittle
Llanbrynmair
POWYS Tel: (01686) 430652
SY19 7BD Fax: (01686) 430441

NRA Project Leader
The NRA's Project Leader for R&D Project 122 was:
Bob Huggins - NRA South Western Region

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EXECUTIVE SUMMARY

In recent years, there have been frequent reports indicating that British agricultural soils are becoming more vulnerable to erosion, mainly due to changes in farming practice, particularly increased use of heavy machinery and increased winter cereals production. The impacts of materials transported away from agricultural land due to soil erosion may be more serious beyond the farm at which it has occurred. These impacts are often termed the "off-farm effects". These include inputs of fine sediment and associated nutrients and pesticides to watercourses.

The aims of this study were to attempt to discern the river sediment load in agricultural catchments and to report methods to reduce or prevent enhancement in river sediment loads from field surfaces. The research approach is a combination of analysis of existing archive data, new field work using manual and automatic bulk sampling, turbidity monitoring and laboratory work to quantify river sediment concentrations and loads. Spatial investigations and short-term field deployments (eg. over one high flow event) are combined with medium-term field sampling campaigns of one year in each of six selected catchments. The selected catchments were the Severn, Wye, Weaver, Hampshire Avon, Allen and Chelmer.

The dynamics of eroded sediment in catchment systems are outlined. The movements from sources to sinks are of three kinds - they can take place across the catchment surface, such as in a field, over variable distances within a channel or across the catchment surface/channel interface. These classes of movement and some of the available models to predict erosion and transport are briefly described.

There has been a large amount of UK work concerned with surface erosion on agricultural land indicating soil erosion rates in the ranging from of 0 - 55.3 t $ha^{-1}y^{-1}$. The estimates of river sediment transport in the study catchments indicate a range of yields from agricultural catchments ranging from 4 t km^{-2} y^{-1} for small upland grassland catchments, 25 t km^{-2} y^{-1} for large scale undisturbed grassland, through varying proportions of mixed grassland and arable, up to dominantly intensive arable yielding 71.6 t km^{-2} y^{-1}. This is on the low to typical range of British catchment yields and probably reflects the relatively low rainfalls experienced during the study period. The exceptionally dry conditions meant that the catchment yields did not include a significant input from field erosion.

Short term reach studies indicated that flood inundation of tilled land in close proximity to the middle reach of the River Severn yielded significantly increased downstream suspended loads throughout the flood curve, with no sign of sediment exhaustion effects. This work provides good evidence to support the principle of minimising tillage in close proximity to stream channels to prevent sediment pollution.

Data from the NRA suspended solids archives proved of little value to this study beyond giving ranges in concentrations on a large spatial scale. Recommendations include the extension of routine measurement of sediment concentrations, eg. through increased use of turbidity measurements.

Methods to prevent or reduce erosion and inputs to streams are considered. These include adjustments to spatial patterns of crop cover, creation of riparian buffers and greater attention to the effects of heavy machinery, such as soil compaction (leading to increased overland flows) and wheelings.. These principles, based upon British and international experience, are also outlined in a generalised form in a proposed guidance note to farmers to prevent soil erosion.

KEY WORDS

AGRICULTURE, EROSION, SUSPENDED SEDIMENT, SOILS

1. PROJECT BACKGROUND

The rates and impacts of soil erosion on agricultural land have received much greater attention in the last decade than in the past. The processes involved in soil erosion by water in Britain are rainsplash, sheet, rill and gully erosion (Evans and Cook 1986). A number of reports have pointed to the problem of soil removal at rates which exceed those of soil development, thereby affecting the productive capacity of farms. Concern has been expressed in the UK and EEC as a whole (eg. Hodges and Arden-Clarke 1987, Roquero 1987).

In addition to movements within fields, e.g. accumulations in ditches, hedge and fence lines, there is also the possibility of movement of material to areas beyond the field or farm. This transport may be due to wind action or flowing water and can deliver sediment to roads, private property and to the principal concern of this report, watercourses. It has been suggested that the impacts of materials transported away from agricultural land due to soil erosion may be more serious beyond the farm at which it has occurred (eg. Evans 1989). These impacts are often termed the "off-farm effects".

Only a limited number of British agricultural soil erosion studies have reported off-farm effects in detail (eg. Evans and Nortcliffe 1978, Reed 1979). Reports have tended to be concentrated upon localised events associated with high intensity rainfall. However there is a wider relevance, as trends in land management practice have also been implicated in the magnitude of the erosion (Boardman 1990). Agricultural intensification is thought to accelerate soil erosion on a large scale through lowering of soil organic matter levels in arable areas (Morgan 1985), compaction (thereby reducing infiltration) and downslope rilling/wheelings on soils, due to use of heavy machinery (Fullen 1985). In pastoral areas soil compaction and loss of vegetation cover occurs in heavily grazed areas. In addition, radical changes in land use towards arable cultivation in traditional pastoral areas, such as the Downlands of southern England, and particularly the change to winter cereals over the last decade has been reported as a major cause of enhanced soil erosion (Boardman 1984).

The justification for this project was the need to assess and review the impacts of soil erosion upon channel water quality and habitat in a range of rivers in England and Wales. In addition, it was considered of value to the NRA to explore methods to ameliorate sediment pollution from agricultural soil erosion.

1.1 Impact upon biota

If the material mobilised by soil erosion is supplied to stream channels, there can be deleterious effects upon channel habitat, including impacts upon both plant and animal life, in addition to water quality. Enhancement of fine sediment concentrations can affect both algae and macrophytes (Cordone and Kelley 1961). Even very thin films of sediment deposited on stream beds can inhibit or eliminate some invertebrate populations (Nuttall 1972), eg. mayflies and stone flies, whilst some species may increase in numbers eg. midge larvae.

Fish may be affected by the silt smothering of spawning beds (Sheldon and Pollock 1966, Milner et al 1985). Salmonids may suffer reduction in the suitable breeding areas and invertebrates to feed upon (Jones 1964). There may also be sub-lethal effects, such as gill damage, in waters with high suspended sediment concentrations (Alabaster and Lloyd 1980). Within the NRA there is notable concern for the impacts of the filling of voids in gravel beds as a deleterious impact upon fisheries habitat (in South Western, Southern and Severn-Trent regions). This effect has been compounded by the long periods of dry weather flows of the last three years which have led to the drying out and consolidation of this bed material matrix into "pavements". Scarification and other gravel cleaning methods are being considered, by NRA and others, to loosen and allow this material to be transported out of problem reaches. However, this practice might also lead to further problems in downstream areas of the channel.

1.2 Impacts upon water quality

As phosphorus and persistent organochlorine pesticides tend to have low solubilities and are readily adsorbed on to soil particles there is often very low levels of these pollutants in waters percolating through soils to rivers (Harrold 1971). However, there is also concern regarding the chemical contaminants, which may be in particulate form or closely associated with soil particles, when these soils are subjected to erosion. Both nutrients and pesticides may, therefore, enter watercourses as parts of this load.

1.2.1 Nutrient inputs from soil erosion

A significant proportion of the nutrient load in rivers can be in particulate form. Although they may be less immediately available for biological uptake, nutrients associated with sediments can be a source for biological production over much longer time scales than nutrients passed through rivers in solution. In the case of phosphorus, which is often a limiting element controlling eutrophication in freshwaters, work in the United States by Sharpley and Smith (1990) has pointed to the selectivity of soil erosion in size ranges of soil entrained which favours phosphorus transport. Most of the phosphate coming off catchment surfaces was found to be in particulate form. An example of the enrichment associated with selective erosion processes has been reported by Thomas, Carraker and Carter (1969) who reported enrichment ratios of 3-6 times in wash off of phosphorus fertiliser from the plough layer of loamy sand soils. Walling and Kane (1984) indicated enrichment ratios between suspended sediment in the River Dart and surface soils on arable land of 1.83 for P and 4.00 for N. In Minnesota, on loam soils, Timmons, Burwell and Holt (1968) reported that, over a two year period, more than two hundred times more total nitrogen was removed from fallow plots by sediment transport than in solution in storm run-off. British studies have also indicated that significant contribution is made to river nutrient loads by suspended sediment transport. Walling and Thornton (1984) have stated that sediment-associated transport accounts for approximately 10% of N and 50% of P in the River Dart and River Exe.

1.2.2 Pesticide inputs from soil erosion

With regard to pesticides, the amounts found in UK river sediments is highly variable. House (1991) has investigated the levels of selected lipophilic pesticides in river sediments. Relatively high concentrations of lindane, deltamethrin, DDT and its metabolites were found in the beds of farm drainage ditches. The movement of some pesticides, eg. DDT and triflurin have been found to be closely related to storm-event sediment discharges (Willis et al. 1983).

The Rosemaunde farm study supported by NRA has been investigating the relatiye importance of particulate and solutional outputs of pesticides from farmland. Data has been collected on the residues of number of widely used pesticides (including atrazine, simazine, mecoprop, lindane and isoproturon) in a range of environmental compartments including soil, soil water, soil biota, drainage water, receiving stream water and biota. Comparisons between the trifluralin transported in suspended sediments, relative to that which was transported in the dissolved phase indicated that suspended sediments accounted for between 8-50% of the total during a storm rainfall event. Concentrations of trifluralin remained low in all bed sediments deposited in traps during and after storm events. A suggested explanation for these results was that the pesticides were mostly attached to the finer particle sizes which were not deposited on the bed within the study reach, which was in the immediate farm area.

Work by the Soil Survey and Land Research Centre (Harrod 19--) has investigated pesticide outputs, including that associated with movements of material from fields to watercourses under bulb and arable cultivations, for South Western Region of NRA.

2. OBJECTIVES

2.1 Overall objectives

The main objective of this study is to identify the factors affecting the yield of suspended sediment within river catchments and to produce recommendations to reduce adverse impacts of soil erosion.

2.2 Specific objectives

a) To identify catchments with a high yield of suspended sediment.
b) To identify factors leading to erosion losses.
c) To estimate whole catchment annual outputs of sediment.
d) To discriminate that part of the yield attributable to soil erosion.
e) To provide bulk samples for further analyses if required (eg. for analyses of particulate chemistry).
f) To compile guidelines for the prevention and amelioration of particulate pollution from soil erosion sources.

3. FIELD DATA COLLECTION

3.1 Catchment selections and descriptions

Field work was carried out on the Rivers Severn (Severn-Trent Region), Wye (Welsh) and Weaver (North-West) in 1991/1992 and Rivers Chelmer (Anglian) Allen and Hampshire Avon (Wessex) in 1992/1993. The choice of catchments was based upon the views and experience of NRA regional staff.

The following conditions were considered desirable:

(a) The presence of intensive arable or mixed agriculture.

(b) The existence of suitable archive data.

(c) Current flow monitoring at suitable points in catchments

(d) The absence of major urban or industrial inputs which would obscure rural particulate inputs.

(e) Perceived soil erosion problems, high river suspended solids or within-channel depositional problems.

Catchment maps are shown in figures 3.1 and 3.2. A brief summary of catchment characteristics is given below:

ALLEN (to Walford Mill). Catchment area 176.5 km^2. Deeply dissected in upper catchment to moderate slopes lower down. Mainly Chalk, with Reading Beds in lower catchment. Thin alluvium, sands and gravels along the river valleys. Some Plateau Drift and Clay with Flints on interfluves. Mixed farming with recent shifts to arable.

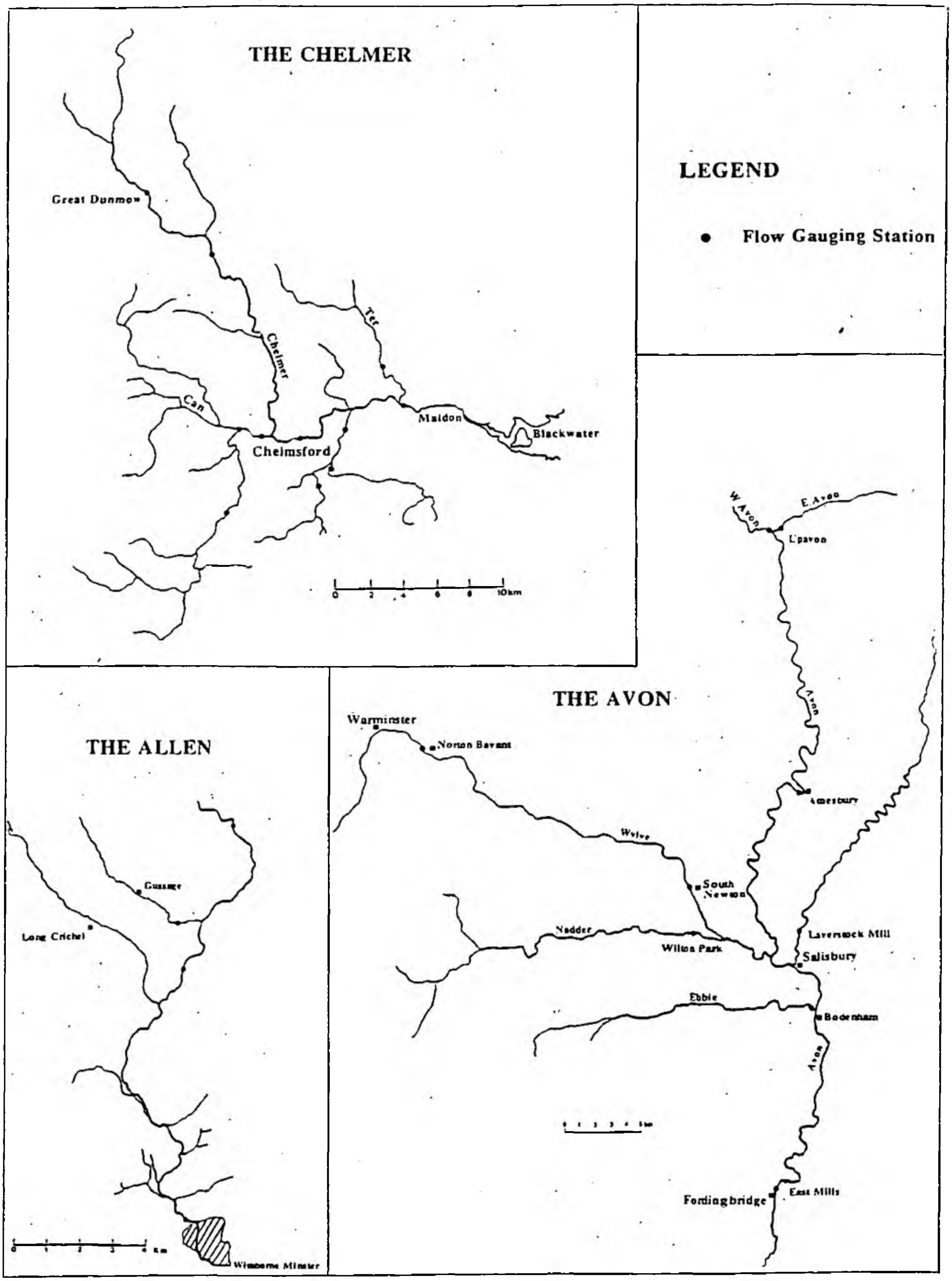
AVON (to East Mills). Catchment area 1477.8 km^2. Mainly Chalk catchment with some Gault Clay and Greensand in upper catchments. Mainly pastoral with a trend toward increasing arable over the last decade.

CHELMER (to Springfield). Catchment area 190km^2. Chalk in upper catchment but mainly London Clay. Relief ranges from upland to low lying gently sloping areas. Dominantly arable with limited pastoral agriculture.

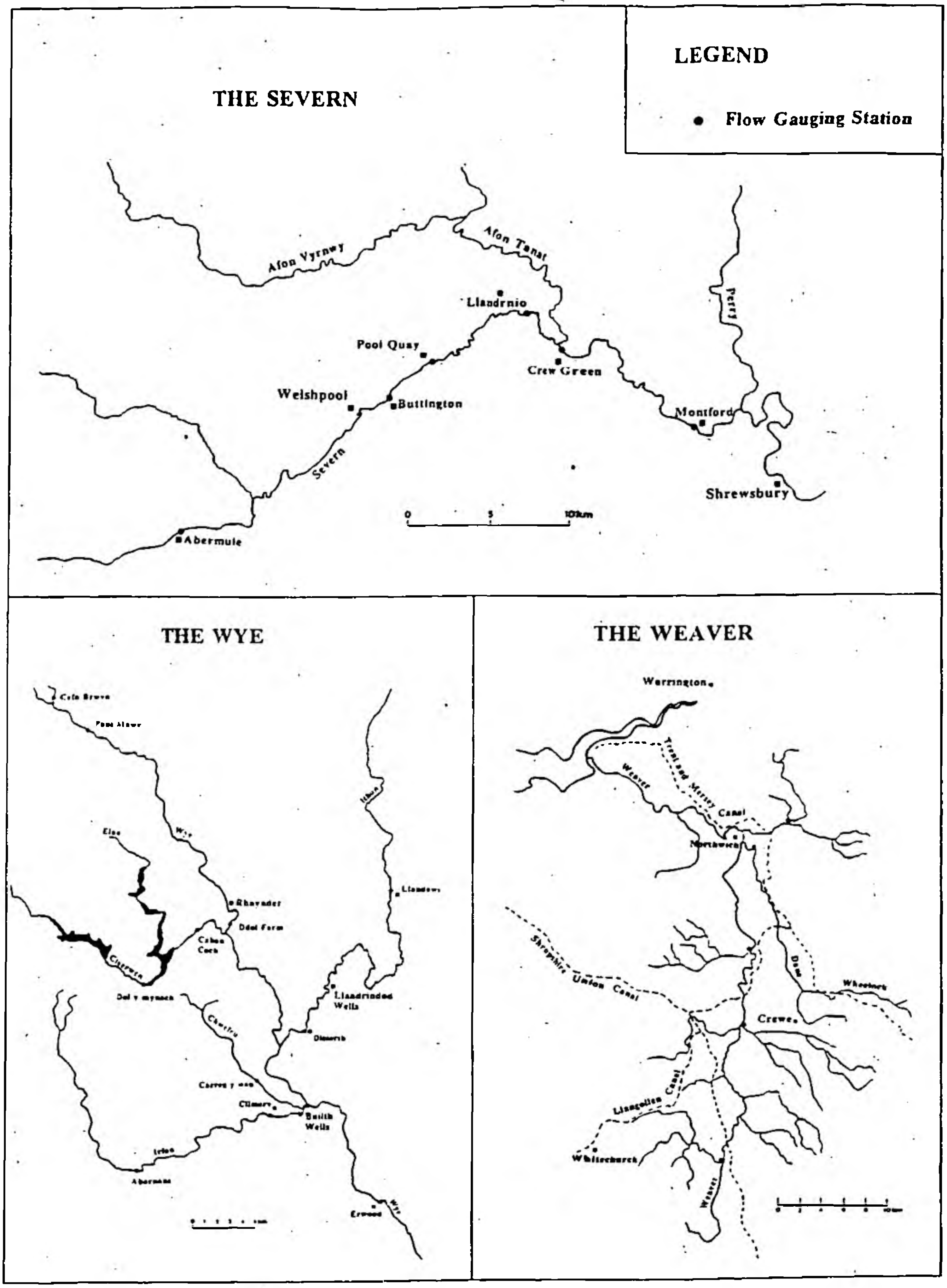
SEVERN (to Montford Bridge). Catchment area 2025 km^2. High relief headwaters with broad bottomed valleys of moderate slope with boulder clays and fluvial gravels. Solid geology is of Ordovician shales and mudstones. Moorland, forestry, pastoral and arable agriculture.

WEAVER (to Ashbrook). Catchment area 622km^2. Mostly a low relief catchment, with mixed agriculture. Post-glacial deposits over Keuper Marl. Farming in large parts of headwaters.

3.1 Locations of study rivers



3.2 Maps of selected study catchments



3.2 Maps of selected study catchments

WYE (to Erwood). Catchment area 1282km^2. Large wet upland catchment draining Palaeozoic sedimentary and igneous geology. Moorland, forestry and dominantly pastoral.

Analysis of false colour Landsat imagery has been carried on the study catchments to identify land use cover. Maximum radiances in 6 wavebands were used. The analysis included 16 classes of land-cover down to 30m x 30m. grid resolution. Examples of the results of this analyses are shown in Figures -- to --. These illustrations show the filtered Landsat imagery. Bare earth and cereals were viewed as the most likely land covers to be associated with major soil erosion. Although these land covers will vary seasonally, November photograph was favoured as this is a time when bare soil is extremely vulnerable to erosion.

3.2 Field instrumentation and sampling sites

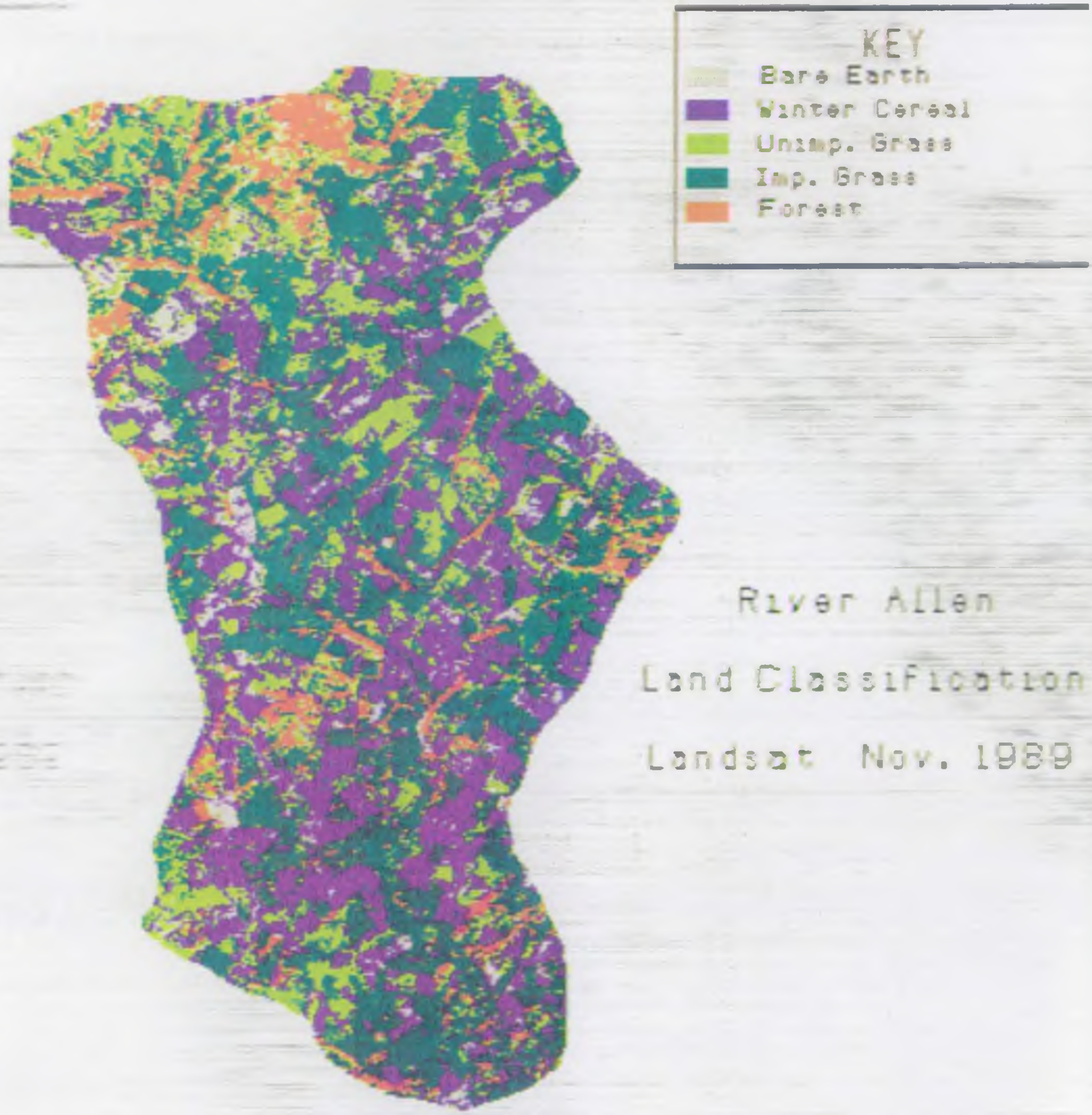
The particulate transport of main interest in this study was the suspended sediment load. This is the fine sediments buoyed up by the flow, varying in size from clays to fine sand. Monitoring techniques ranged from instantaneous manual spot samples to continuous turbidity measurements. These sampling methods are described below:

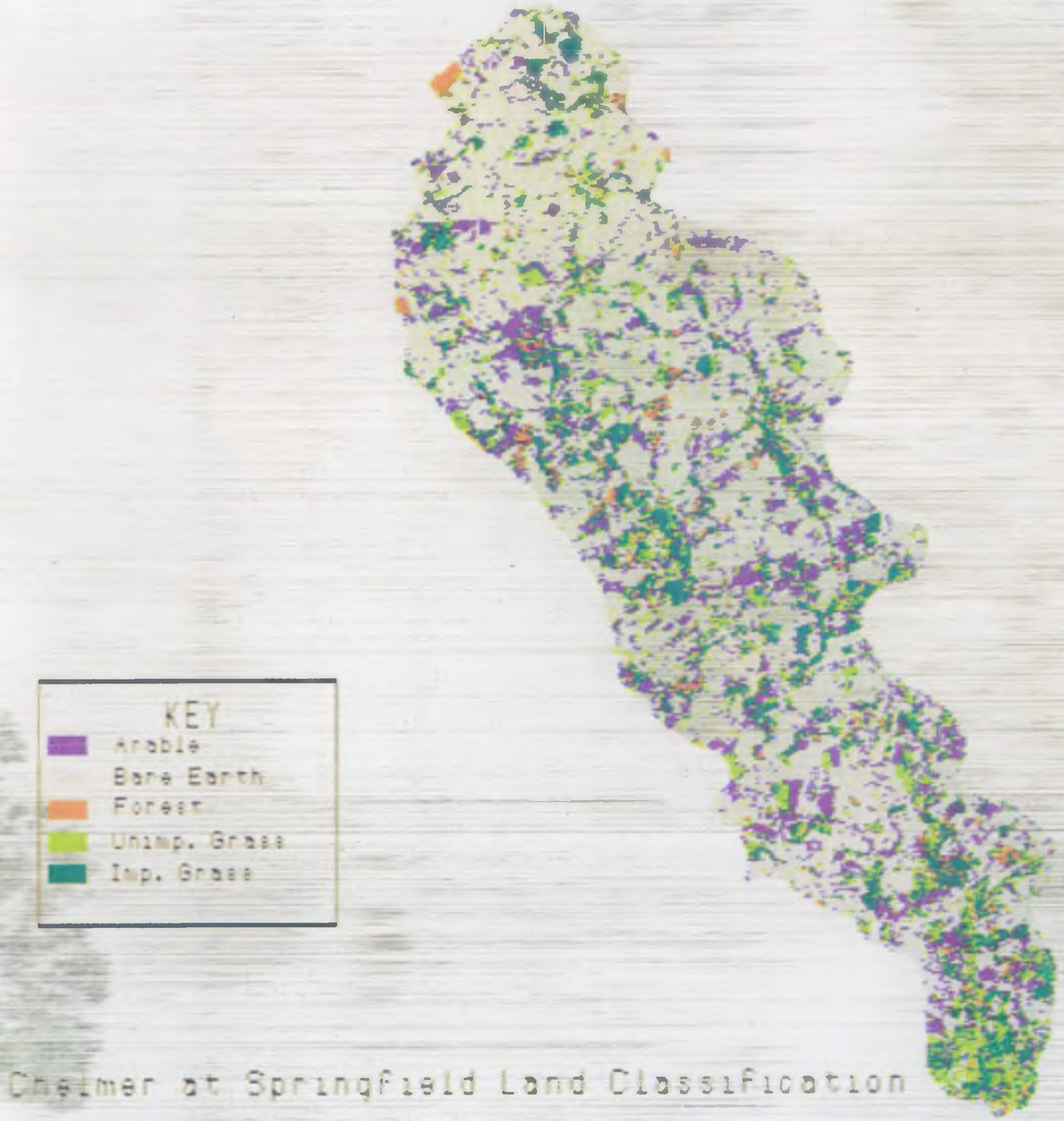
3.2.1 Bulk samplers

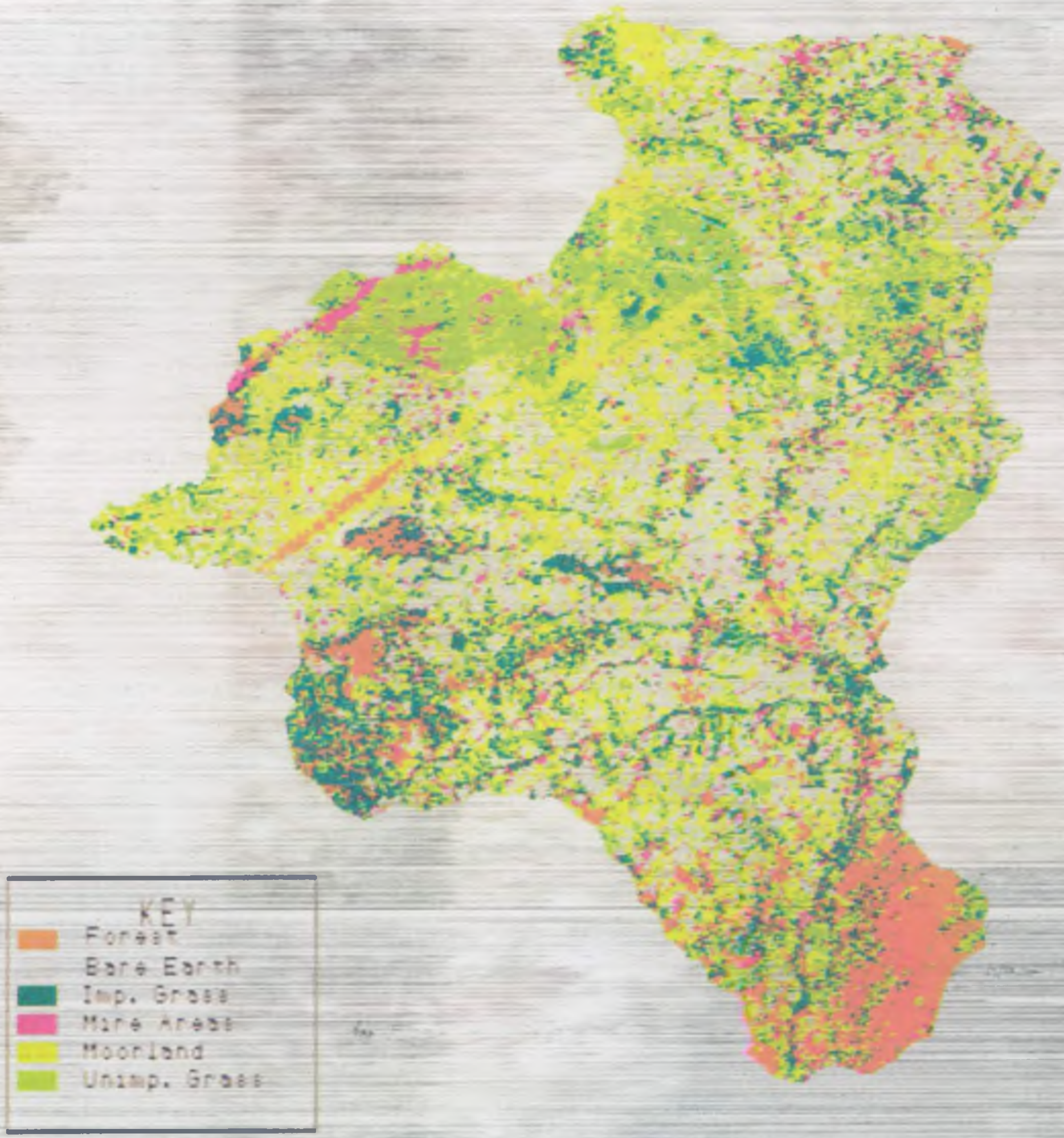
The simplest technique to provide a bulk sample for laboratory analysis is to take a "bucket" or "gulp" sample (fill a wide-necked bottle direct from a stream). This technique is most acceptable where suspended sediment is known to be distributed evenly across the cross-section. This has been observed in some upland channels (Hall 1964 and Bathurst et al 1986) which are often highly turbulent during high flows. However, where there is likely to be significant variations in the concentration across the river section, depth integrating samplers designed by the United States Geological Survey have been used (Guy and Norman 1970). These are lowered and raised slowly at a constant rate at a number of verticals across the channel to provide more representative samples. These samplers have the advantage of being highly portable.

Automatic bulk samplers have the advantage of being less labour intensive in the field and can be triggered during events at preset flow levels. Given the wide geographic spread of the study catchments, this was very valuable, as it was not possible for the field team to respond to every event. In this study the 24 x 500ml version of the EPIC 1011 sampler with waste water sampling chambers has been used. The 24 bottles are divided into 4 stage-triggered runs, taking samples every 15 minutes. The stage triggering was by float switches set up on gauge boards. Battery power was topped up using solar panels to ensure that the instruments performed, without frequent visits, following long periods of dry weather. The waste water sampling chambers are funnel-shaped with a reasonably wide bore tubing to prevent storage of particulate material within the sampler chamber or tubing, thereby minimising loss or contamination of water/sediment samples.

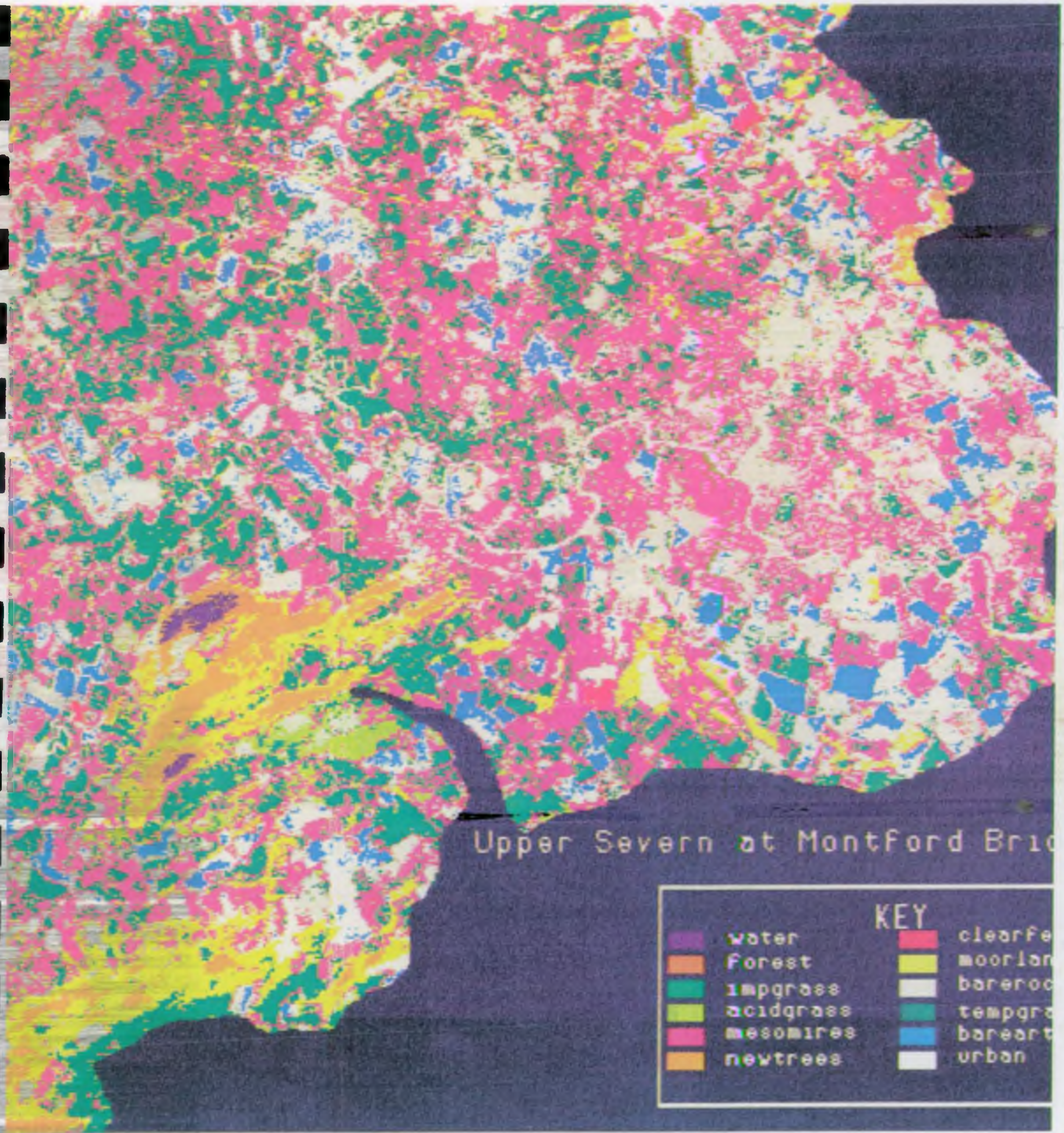
The bulk samples were analysed using vacuum filtration techniques. Bulk samples are time-consuming to analyse, but do provide material which may be subjected to further analysis,

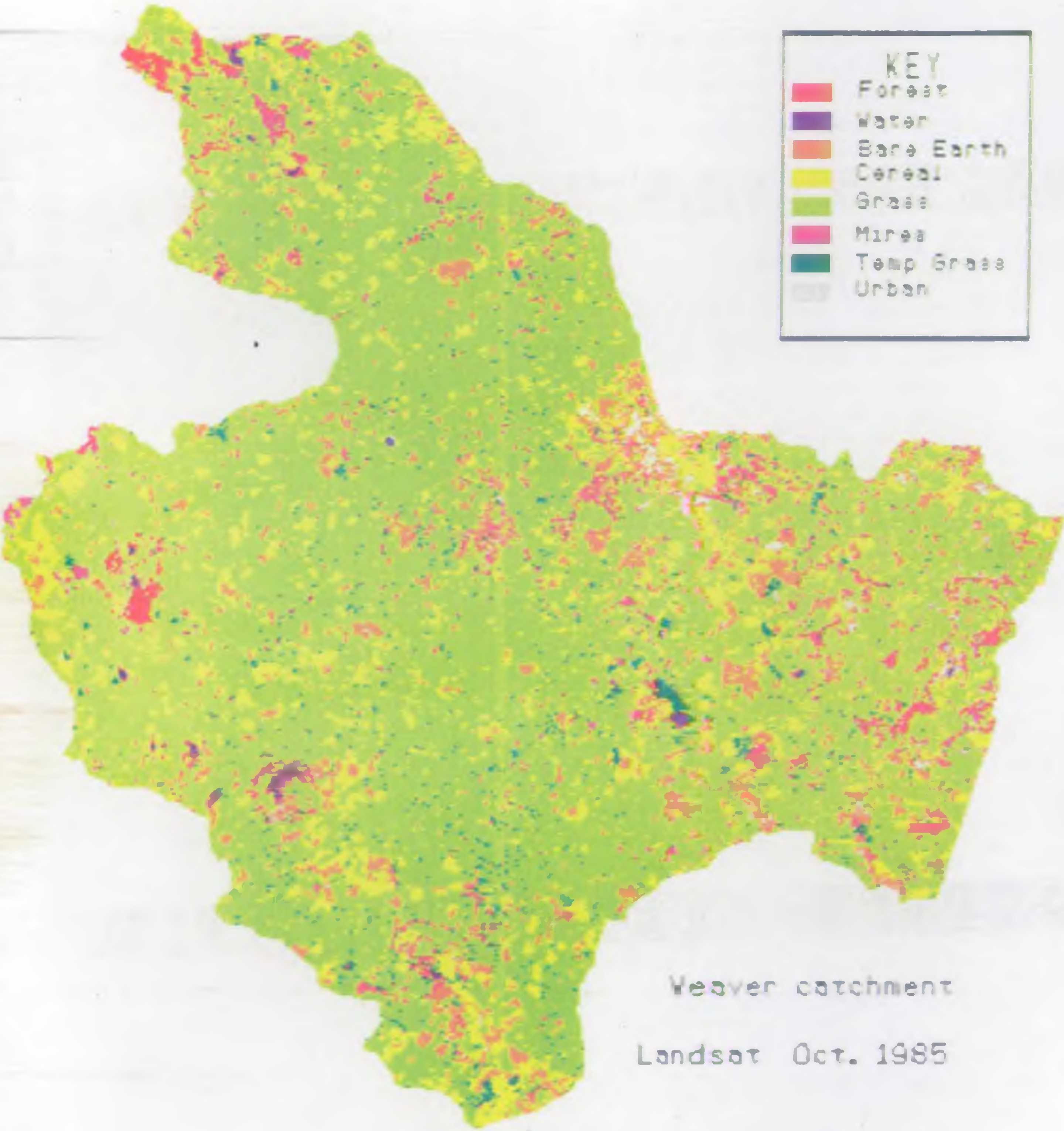

KEY
Bare Earth
Winter Cereal
Unimp. Grass
Imp. Grass
Forest
River Allen
Land Classification
Landsat Nov. 1989


KEY
Arable
Bare Earth
Forest
Unimp. Grass
Imp. Grass
Chelmer at Springfield Land Classification



The Dorset Avon Land classification Aug. 1984


Upper Severn at Montford Bri
KEY
water
forest
impgrass
acidgrass
mesomires
newtrees
clearfe
moorlan
bareroc
tempgra
bareart
urban


KEY
Forest
Water
Bare Earth
Cereal
Grass
Mires
Temp Grass
Urban
Weaver catchment
Landsat Oct. 1985

after the physical measurement of sediment concentrations, if required.

3.2.2 Turbidity measurement

Turbidometry provides an alternative to the collection of large numbers of bulk samples, but does not provide a direct measure of sediment concentration. Turbidity represents the cloudiness of the river water and can be calibrated within limits as an indirect measure of suspended sediment concentration (Eden 1965, Thorn and Burt, 1975 and HMSO, 1981). The value of the calibration varies from site-to-site and from flood-to-flood, dependent upon the characteristics of sediments in transport. Calibration is particularly sensitive to particle size and colour variations.

The main instruments used in this study were the Partech absorptiometric infra-red sensors with Grant squirrel loggers. These were set to give 5-15 minute values for turbidity. This is a very flexible system which is internally powered and yields immediate data. There is, as stated above, a need for calibration with bulk samples to allow for variations in the relationship between sediment concentration and turbidity. In addition, as is also the case with instantaneous bulk samples, the distribution of sediment though the river cross-section needs to be taken into account where this is possible. Some field installations suffered vandalism problems. Where this occurred or seemed likely, equipment was concealed short distances upstream of gauging stations.

4. SOURCES, DELIVERY AND CONVEYANCE OF SEDIMENT THROUGH RIVERS

There are a number of potential sources of sediments which contribute to the particulate material observed in watercourses. These include sediments which are removed from the catchment surface, from within channel sources (the bed and banks) and from effluents; domestic, agricultural and industrial.

In consideration of the impacts of agricultural soil erosion, it is necessary to describe the underlying "natural" sediment system, highlighting principles and uncertainties which are of specific interest to this study. The routing of particulates through catchment systems involves both catchment surface and channel processes. These can be enhanced or reduced by human actions.

The dynamics of sediment are determined by the availability of materials for entrainment, the transport to another location and eventual deposition. The movements from sources to sinks are of three kinds - they can take place across the catchment surface, such as in a field, over variable distances within a channel or across the catchment surface/channel interface. These classes of movement and some of the available models to predict erosion and transport are briefly described below:

4.1 Movement of sediment over the catchment surface

The erosion or production of sediment from the surface soils is affected by many factors such as rainfall inputs, vegetation, surface topography, soil hydrological and mechanical properties. These will vary through time in accordance with natural events (eg. storm rainfalls) and man induced effects, (such as tillage and cropping). There has been a large amount of UK work concerned with surface erosion on agricultural land (eg Boardman 1984, 1986, Evans 1977, Evans and Cook 1986 and Morgan 1980, 1985). This work has indicated soil erosion rates in the range of 0 - 55.3 t $ha^{-1}y^{-1}$.

Soil erosion surveys have also been carried out using measurements of depletion or enrichment of a range of magnetic, geochemical and radionuclide labels. These techniques can be used to indicate redistribution of soil at a range of scales including plot-scale, field scale and catchment scales (eg. Fullen 1985, Walling and Quine 1992). They can also be linked to the properties of stream sediment loads to infer possible sediment sources eg. Walling and Woodward (1990) and Bonnett and Leeks (1989). In general, work by Walling and Bradley (1988) in the South West has indicated a dominance of field surfaces as a source of river suspended sediments, whilst work in the upper parts of the River Severn have indicated dominance of bank, drain and channel sources (Arkell et al. 1983, Bonnett et al. 1989). These studies have therefore emphasised the spatial variability in soil erosion at the local field and plot scales, and regional variations in the dominant sources of stream suspended sediments.

4.2 The movement of material from catchment surfaces to the channel network

Walling (1990) has highlighted the disparity between the reported rates for soil erosion and the observed rates of transport observed in British rivers. Erosion rates appear to be at least an order of magnitude higher than rates reported to be transported by rivers. This contrast partly reflects the fact that the sediment supplied to rivers is an integration of the supplies from highly eroding areas and other areas which experience much lower rates of erosion. This disparity also reflects variations in what is termed the "delivery ratio" which is described below.

The delivery of material mobilised on the catchment surface to that which passes downstream through the stream system is referred to as the "delivery ratio". This can vary from nearly nothing up to almost 100%. Proximity to watercourses, angle of slope and other aspects of local topography, soil moisture and riparian vegetation are critical factors affecting delivery of materials to the stream (J.D. Phillips 1989 and Muscutt et al. 1992). Partial area contributions directed via drains, tracks and wheelings provide rapid routeways for sediment from fields to streams. There are also regional variations in the sediment sources. The literature is rather sparse, but includes the tracer work by Walling (1990), Bonnet et al (1989) and Arkell et al (1984). Walling et al (1983) found most material in transport in the River Exe was derived from field surfaces, whereas Welsh studies by Arkell et al (1983) and Lawler (1986) reported the dominant source as being from stream banks. Walling (1990) also noted that comparisons in sediment size indicated that the material which eventually reached the river was of finer particle sizes than the catchment surface materials, thereby indicating preferential transport.

Dickinson et al (1990) noted, from modelling studies in rolling upland in Ontario, Canada, that up to 85% of the catchment sediment load was emanating from less than 10% of the catchment area. This is an important point with regard to catchment management, as it suggests there may be value in the targeting of preventive measures upon the source areas which are the most likely to result in delivery of sediment to stream networks, assuming these can be identified.

4.3 Within channel movements

With increasing distance downstream, and larger catchment areas, further reductions in the delivery ratio will be expected as there are more opportunities for transported sediment to move into channel storage, in shoals or bars, or to be incorporated into banks or the floodplain. Therefore storage opportunities may reduce the significance of any given physical input of material eroded from part of the catchment surface. Channel processes may also lead to the decay, degradation, transformation, or masking (through burial) of some contaminants. Conversely, storage of parts of the sediment inputs can result in cumulative effects, e.g. through selective deposition of particular size grades and densities.

Large inputs of sediment may also cause adjustments to channel geometry and planform, which will in turn feedback to sediment dynamics by initiating further channel erosion. For

example, increases in storage associated with enhanced inputs of sediment to channels may cause channels to increase in width (Newson and Leeks 1987).

Large scale channel planfom adjustments may take place over years to decadal timescales. Within-channel movements over shorter timescales are also important but have rarely reported. The movement of sediment waves associated with particular erosive events are not well understood. Studies in the area of empirical measurement of the movements of sediment waves through catchment networks (eg. Gilvear and Petts 1987, Leeks and Newson 1989) have been very limited in number and spatial scale.

4.4 Modelling of agricultural erosion within catchments

Although model development was outside the brief of his study, it should be noted that there are several major model development programmes taking place which are relevant to this project, which may in the longer term provide predictions of erosion and provide estimates of delivery and conveyance through channels. Many of these are N. American in origin and are only beginning to be applied to British conditions. Many of the erosion prediction models have been based upon the empirically based Universal Soil Loss Equation (USLE) developed and applied in the USA by many agencies. This equation computes an annual erosion rate as a product of factor values that represent climatic erosivity, soil erodibility, topography and land use conditions. Morgan (1986) reviewed the problems associated with use of USLE and advised against its use outside the eastern parts of the USA. An intention of this study was to apply the latest version of the Watershed Erosion Protection Project Model (WEPP), currently being developed by the United States Department of Agriculture. Release of this model has been delayed. Another model is GAMES which is the Guelph model for evaluating the effects of Agricultural Management systems in Erosion and Sedimentation which was developed as a watershed management screening tool (Dickinson W.T., Wall G.J. and Rudra 1990). In application to UK, GAMES has been found to overpredict delivery to streams (Boardman 1991). Morgan(1986) found the CREAMS model of value in British conditions with 4 out of seven test sites giving mean annual erosion rates of the right order of magnitude in comparison with observed data. There is also currently a model being developed at Silsoe for applications within the EEC.

General criticisms of the models available to date has been that they have subject to very limited field testing. Calibration has tended to be based upon small scale plots rather than fields (let alone catchment scales!) and they have tended to be restricted in application to small scales in particular regions. Foster (1990) has pointed to the value of the development of a new generation of process-based models. Widespread use of such models at field and catchment scale were viewed as unlikely in the foreseeable by Harris and Boardman (1990).

The integration of erosion and delivery with channel transport models such as QUASAR is taking place within the NERC Land-Ocean Interaction Study to show movements of a range of determinands through river basins. However this work is at to early stage to be applied in this study. In summary, increasingly sophisticated models are being developed to represent the movements of sediments through catchments, but all require further development and to date here has been only limited testing in British conditions.

5. RESULTS OF FIELD STUDIES

5.1 Monitoring results from catchment studies

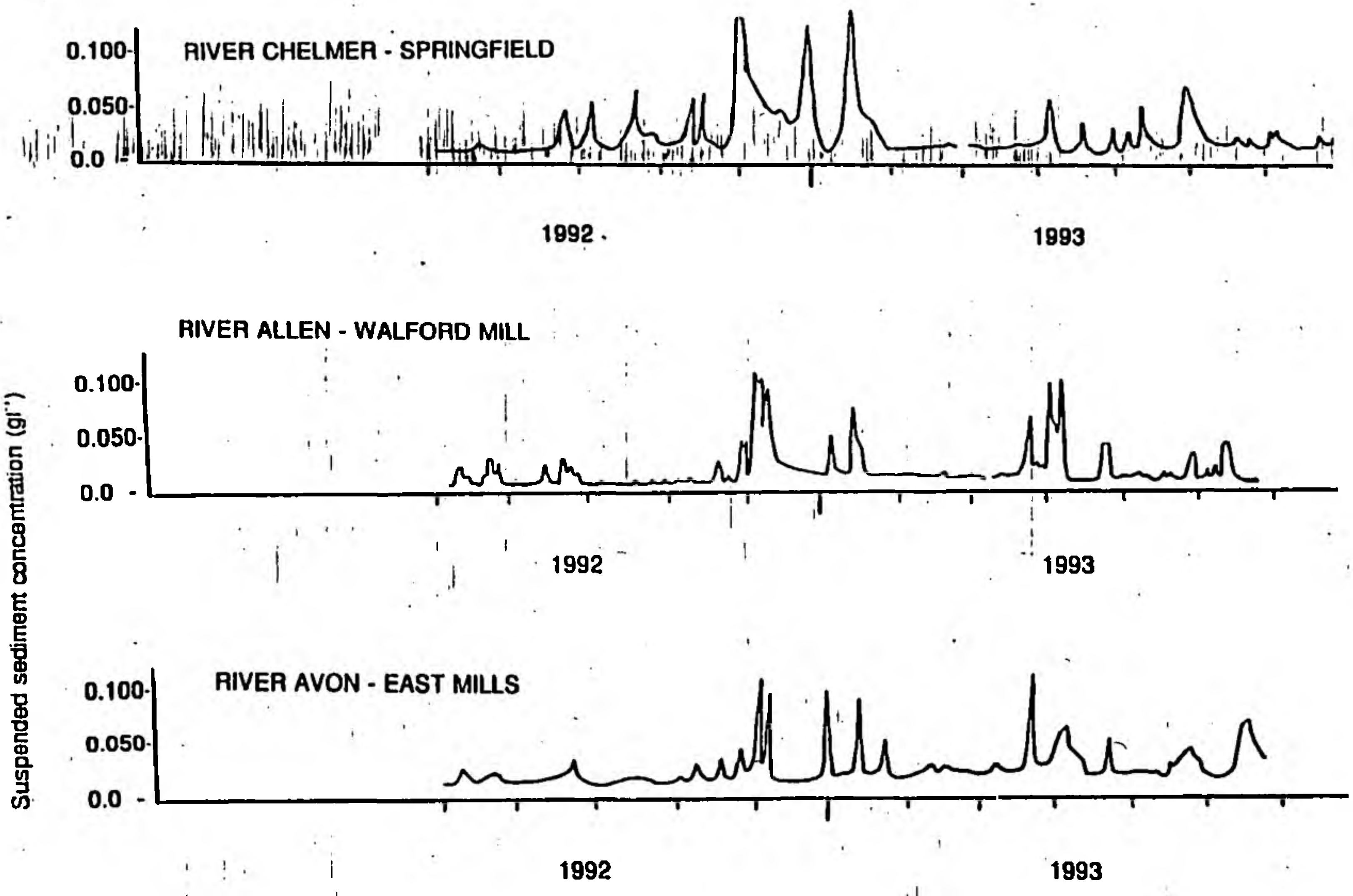
From spring 1991 to summer 1992 the monitoring programme was concentrated upon the rivers Severn, Weaver and Wye. This was a period of exceptionally low rainfalls in each of the study catchments.

The low rainfalls experienced during this current study meant that this was also a period of extremely low sediment mobility, both on catchment surfaces and in river channels. For each catchment, the sediment transport data was therefore much sparser than the project team could reasonably have anticipated. The period of monitoring was extended in to the summer of 1992 in the hope that additional data would be forthcoming from the field stations. However the sediment transport yields remained atypically low. In the case of the Wye and the Severn it has been possible to supplant this data with longer term data from NRA and IH. However in the case of the Weaver, this is not available and existing suspended solids data is insufficient to produce comparable sediment yield estimates.

The second phase of medium-term field monitoring began on the Allen, Chelmer and Hampshire Avon in summer 1992. This proved to be a far more useful study period relative to the first field monitoring phase. Curves based upon continuous turbidity measurements, calibrated against automatic bulk samplers and manual sampling are shown in Figure --. Annual yield estimates were as listed below and discussed in section 6.

Table 5.1 - Annual Yields from selected catchments

Location	Tonnes of suspended sediment per year
Severn at Abermule	23,780
Wye at Erwood	31,780
Avon at East Mills	84,574
Allen, Walford Mill	8,298
Chelmer at Springfield	13,609



5.1 Suspended sediment concentrations in study rivers.

5.2 Results from short term reach deployment

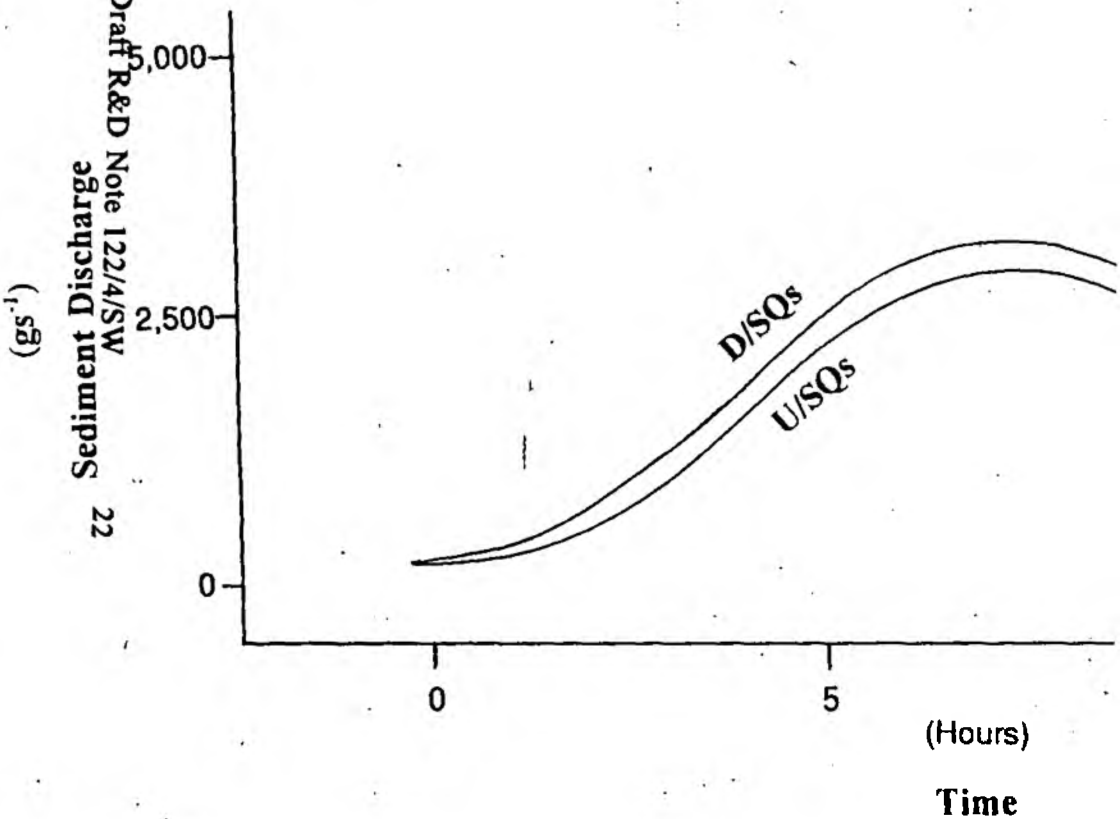
Field monitoring of soil erosion events leading to inputs to watercourses requires highly flexible sampling strategies as both spatial and temporal distributions tend to be very erratic. Throughout this study, it was the intention of the project team to make sampling routines responsive to rainfall and flow events. In addition, where field observations suggested there was increased probability of erosional events, eg. at sites where a particular land use practice was likely to increase erosion risk, intensive short term monitoring was carried out.

Three out of the four occasions when instrumentation was deployed for short term monitoring, eg. of wheelings leading to a watercourse and tillage of vulnerable soils near watercourses, significant rainfalls did occur before stabilisation by vegetational cover. However on one occasion useful observations were made concerning the patterns and impacts of outputs of fine sediment from inundated tilled land.

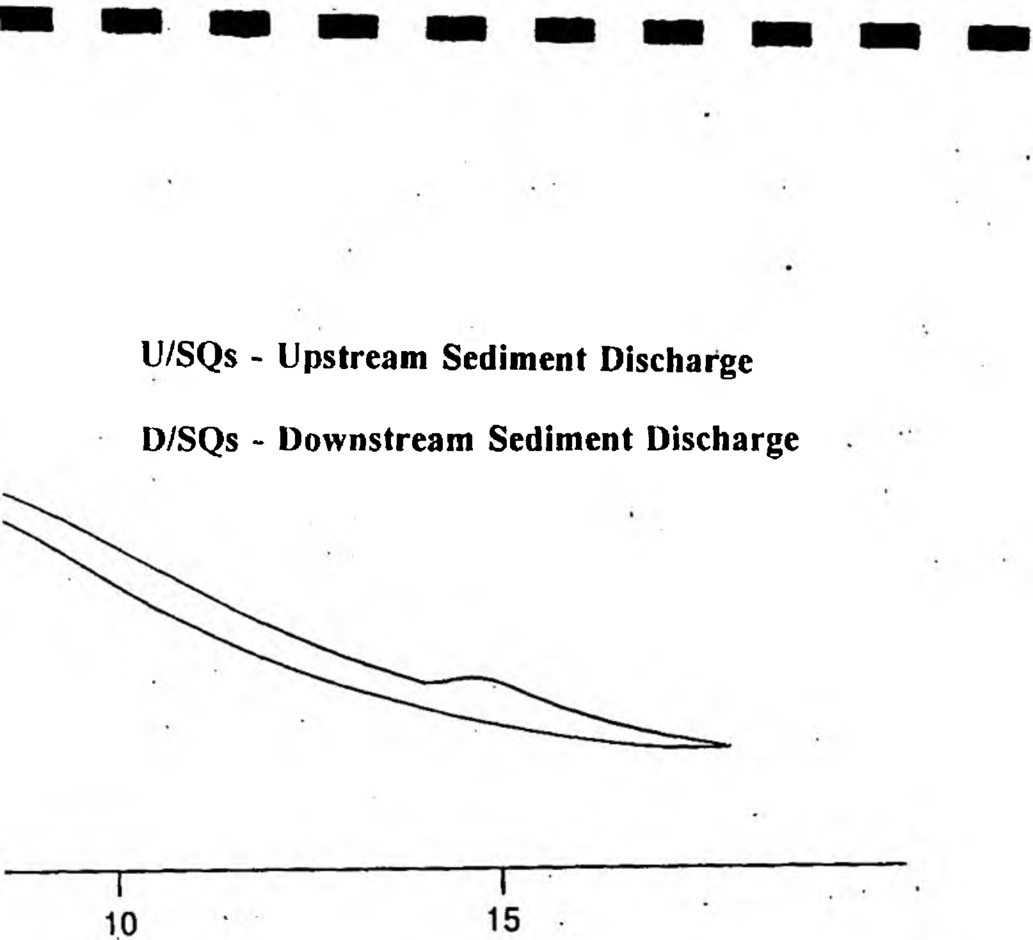
At a site in the middle reaches of the river Severn, between Caersws and Newtown, tillage was carried out right up to a low 200m. length of river bank during March 1991. Bulk samplers were placed immediately above, and 400m. downstream of this site. No other significant sediment inputs were found between these two points. The downstream distance was chosen in the hope that suspended sediment would become well-mixed through the cross section, before the site of the downstream bulk sampler. This was confirmed by checks using manual sampling across the river. Automatic bulk samples were taken at hourly intervals, throughout a moderately high flood event, which inundated part of the tilled field on the night of 18 March 1991.

Figure 5.2 shows the sediment discharge curves for the two sampling sites. The values for discharge from an upstream gauging station were used at both sites. Upstream of the tillage, the river suspended sediment load increased from a value of 228 g s^{-1} up to a peak suspended sediment discharge of 3186 g s^{-1} seven and a half hours later, very close to the flood peak. Suspended sediment discharge then fell during the recession to similar levels to those prior to the flood. In contrast, downstream of the tillage, within 30 minutes of the beginning of the flood rise, significantly higher suspended sediment discharges were apparent. For example, two and a half hours in to the flow event upstream suspended sediment discharge was 507 g s^{-1} whilst the downstream value was 864 g s^{-1}. The downstream peak suspended sediment discharge was 3364 g s^{-1}. The consistency of the results, given that the sample bottles from the two sites were not separated during the laboratory analyses and good agreement between manual and automatic samples, indicate that the disparity between upstream and downstream sites was an accurate reflection of the variations in river suspended load. Therefore, it can be concluded that with the absence of any other significant sediment source within the reach, there was a substantial addition to the sediment discharge of the river throughout the flood from the easily erodible tilled soils. Areas of the field surface subject to inundation appeared to be smoothed off, indicating that eroded material had been removed by sheetwash or hydraulic entrainment by the "broad" flow of the river, rather than localised gully or rill erosion.

It had been anticipated that the site was sufficiently small scale to cause a minor short-lived spike in suspended load, as the loosest material was removed from the field surface.



5.2 Suspended sediment discharge in short reach of River Severn above Newtown, above and below ploughed bank side, 18 January 1991 .


U/SQs - Upstream Sediment Discharge
D/SQs - Downstream Sediment Discharge
10
15

This would be followed by exhaustion of supply as layers of less easily erodible material was reached. It was therefore surprising to find that, as is apparent in figure --, this effect was sustained over 18 hours. Given that tilled area represented only 200m of one bank, it appears likely that much greater impacts would be likely where this practice of ploughing to the rivers edge is more widespread. From a catchment management viewpoint, this study gives support to the principle that ploughing to bank edges should be actively discouraged.

6. DISCUSSION

6.1 Comparison of field results with suspended solids archives

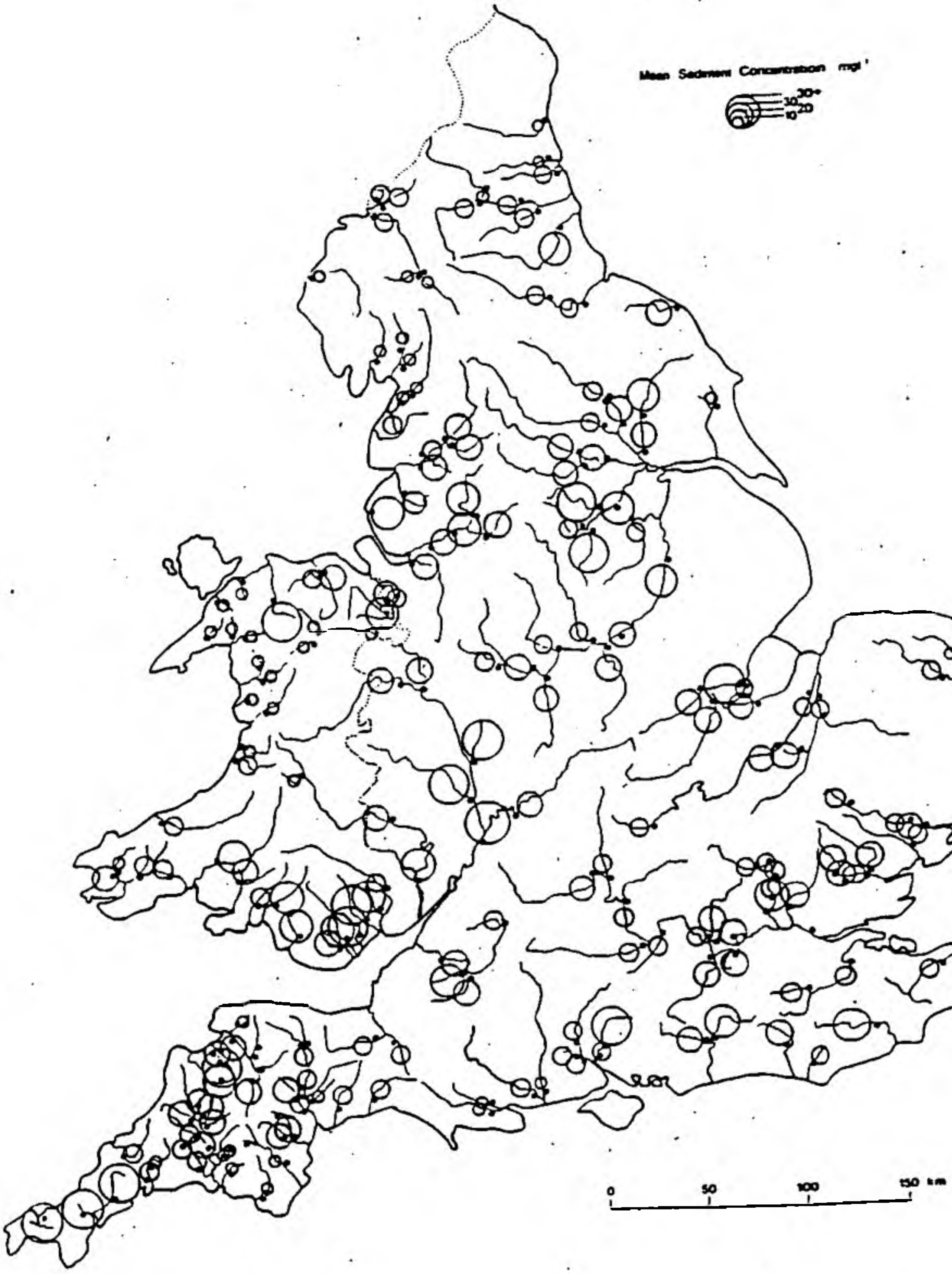
As part of this study it has been important to assess the data which is available at a national and regional level on river suspended loads. The purpose of the trawl was to set the experimental results from this study in to a national context. Some routine monitoring of suspended sediment has been carried for research purposes in England and Wales, of which studies of the Severn (Leeks 1983, Newson and Leeks 1987) and particularly the Exe (Walling 1984 and Walling and Webb 1987) have been the most long-term. The spatial cover from research elsewhere is rather sporadic. It was for this reason that it was decided to assess the available NRA suspended solids archives for the purpose of investigating catchment sediment loads. It must be stated that this data was obviously not originally intended to be used for this purpose.

Within each NRA region, suspended solids data is available. However the trawl revealed that the intensity of measurement, the length, coverage and accessibility of long-term records is very variable. Flow-related sampling of suspended sediments has been very rarely carried out by the Water Authorities or NRA, even for limited periods. This is unfortunate as suspended sediment concentrations in water-courses are usually strongly related to water discharge.

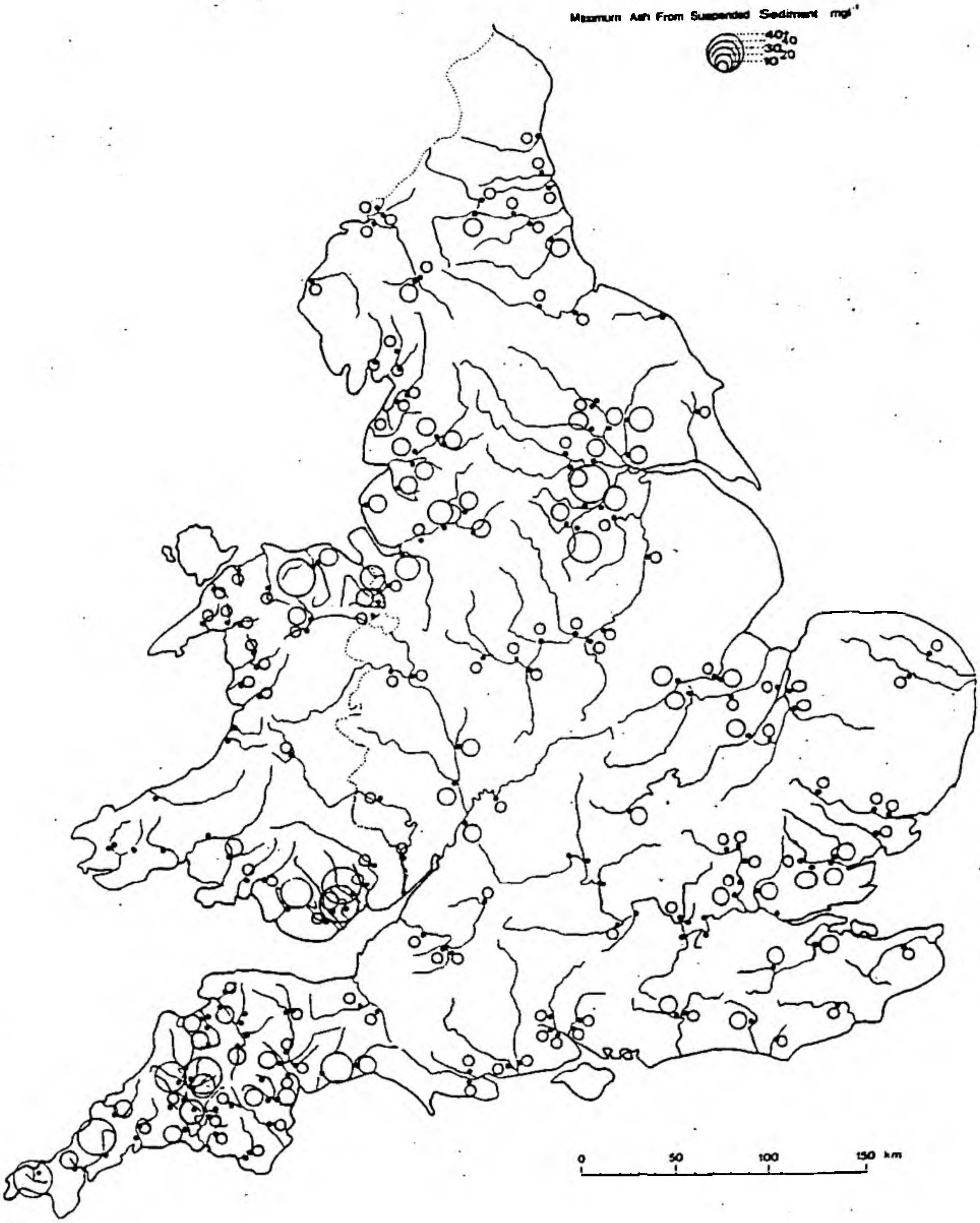
There are a number of other problems in many of the older Water Authority archives. Water discharge and water quality data, including suspended solids, has been compiled separately and cannot be easily related, sometimes with disparity in the positions of sampling stations. A notable development since the formation of the NRA, has been the increasingly close relationship between hydrometric and water quality data gathering and archiving. The analytical methods used to determine suspended solids or turbidity are often not very clear. Data on cross-sectional variations at measurement stations are not available. To derive a convincing relationship between magnitudes of water discharge and suspended sediment, it is necessary to have a reasonable spread of data across the discharge range. This means that in using the routine weekly, two weekly or monthly data, long runs of data are required, with much of the data relating to moderate to low flow conditions, when very little sediment is usually being transported. The record available for most catchments has been found to be inadequate for sediment yield estimation.

Interpretation of the suspended solids records must also recognise that part of the measured concentrations will be derived from biological processes within the water-course, e.g. due to algal productivity. For this reason both total suspended solids and ash from suspended solids have been compiled where both values are available. The data trawled from this exercise is generalised and illustrated in figs. 6.1 to 6.4. A difficulty in interpretation of the spatial patterns is that in many catchments, in addition to inputs of material eroded from field surfaces and bank erosion, particulate materials from industrial and domestic effluent sources are also significant inputs. There are also discontinuities and variations in the sampling frequencies. For most sites a fifteen years of record was obtained. However the start and end dates cannot be specified as these varied from catchment to catchment in a non-systematic way.

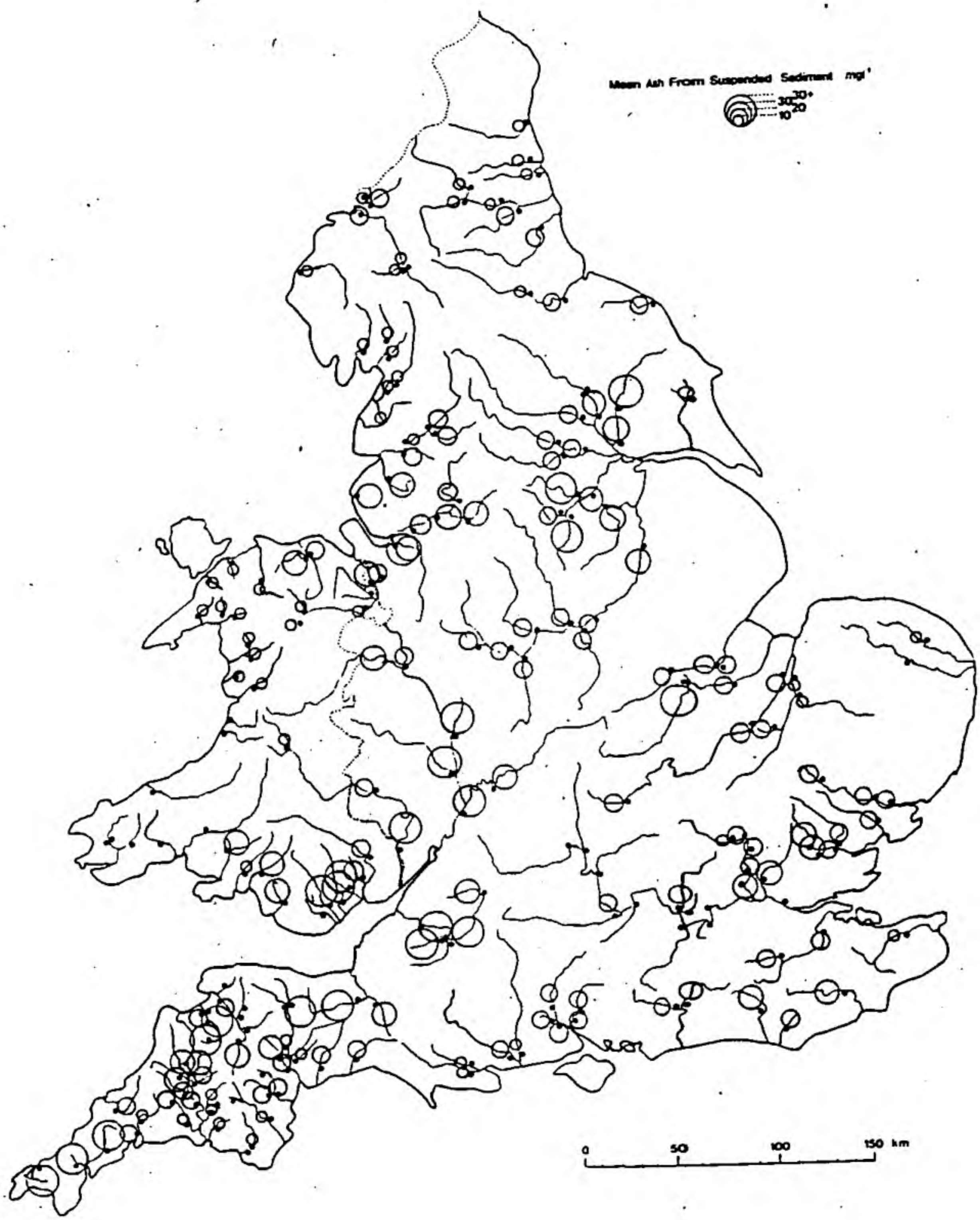
6.1 Spatial distribution of river suspended solids concentrations over 15 year period - Maximum recorded suspended solids concentrations.



6.2 Spatial distribution of river suspended solids concentrations over 15 year period - Mean recorded suspended solids concentrations.



6.3 **Spatial distribution of river suspended solids concentrations over 15 year period - Maximum recorded ash from suspended solids concentrations.**



6.4 Spatial distribution of river suspended solids concentrations over 15 year period - Mean recorded ash from suspended solids concentrations.

The variations in measured concentrations through time were also investigated. Some of the selected archive data for England and Wales appears to show a rise in suspended solids concentrations coincident with the increase in winter cereals of the late 1970's and early 1980's. However, there are also many catchments which show contrary or unclear trends. Although the project team looked at the long term data from each harmonised monitoring site in England and Wales, it was apparent that the data was of insufficient frequency for further analyses to be worthwhile to prove or disprove this hypothesis on a wide scale. There are a number of reasons why suspended sediment levels may be elevated and, as mentioned above, the available archive data gives a very limited impression of the range in suspended solids concentrations in most streams.

6.2 Land use impacts upon river suspended sediment loads

It is unfortunate that the period of field work coincided with a period of exceptionally low rainfalls. This means that the results cannot be viewed as necessarily representing the sediment outputs which may be apparent in more"typical conditions" and must be interpreted with some caution. However, the available data does show contrasts between catchments with differing land uses which are in line with other British work and give support to the consideration of a number of land use and catchment management issues.

As indicated in section 5, the estimates for the Wye and Severn are supported from additional data sources. The Weaver has been omitted as neither the field or available archive data is sufficient to give valid estimates of sediment outputs.

The Severn at Abermule has a mean annual yield of 23,780 t yr^{-1} which gives a per unit catchment area value of 41 t km^{-2} yr^{-1}. These values are for the middle reaches in which pasture land use is dominant. In addition to middle reach estimates, it is also possible to give values for upland sediment yields. These range from 25 t km^{-2} yr^{-1} up to 140 t km^{-2} yr^{-1} in subcatchments with areas between 1-10 km^2 The highest yields are associated with measurements of clearfelling forestry activity in the small Severn headwaters subcatchments, whilst the lower values represent suspended sediment yields from relatively undisturbed mature forested upland catchments.

The yields from the Wye are lower again, as the surface of the Wye catchment above Erwood is less subject to disturbance than the Severn. The mean annual yield of suspended sediment at Erwood is 31,780 t y^{-1} (24 t km^{-2} y^{-1}). Headwaters catchment yields, under rough and improved pasture vary from 3.5-10 t km^{-2} y^{-1}. These Wye results may be viewed cautiously as of the order of the background levels which may be anticipated, given minimum levels of ground disturbance in British rivers, although other factors such as river stability and erodibility of soils may also need to be considered.

In both the Wye and Severn some sediments are held back by reservoirs, Elan Valley and Clywedog. On occasions during large releases, flows from these reservoirs can be a source of suspended sediments (eg.during scour valve releases) or may lead to entrainment of fine material already supplied to the channel (eg. Gilvear and Petts 1987, Leeks and Newson 1989). However, these impoundments represent only minor parts of the total catchment areas at Erwood and Abermule and major impacts upon particulate concentrations were not observed during the year of study.

The Hampshire Avon at Fordingbridge yielded 84,574 t y^{-1} in 1992/1993. This is equivalent to 57.23 t km^{-2} y^{-1}. This is slightly above the typical UK yields. The continuous curve in figure -- indicates that the highest yields occurred in December and January. Suspended sediment concentrations at lower flow levels also tend to be higher than in the other similar sized study catchments, the Wye and Severn. This is also seen in the NRA routine sampling data archive. The major subcatchments which join the Avon near Salisbury showed a wide range of suspended sediment concentrations in response to rainfall, reflecting variations in geology, soils between catchments, and land use. However it did not prove possible to separate the impacts of these variables as they were not sufficiently constant within subcatchments.

The Allen and Chelmer rivers present contrasting catchments, the former dominated by chalk and the latter by the London Clay.. The major study sites were at similar catchment scales (approaching 200 km^2). Dr. Boardman of Oxford University has carried out a reconnaissance study to assess likely sources of sediment within the Allen catchment. The sampling strategies were based on his report (Boardman 1992). The Allen at Walford Mill, near Wimborne, yielded 8298.5 t. (47 t km^{-2} y^{-1}) in 1992/93. The suspended load variations in the Allen exhibit a fairly complex response to rainfall events, which have implications for the dynamics of sediment. The sediment concentration curve tends to involve multiple peaks following rainfall. The first and largest peak is probably associated with catchment surface flows. It occurs approximately one day before a lagged channel flow peak (associated with the elevation of groundwater levels). A secondary peak or sustaining of high sediment concentrations also takes place with the lagged channel flow peak, probably as rising channel flow entrains materials stored within the channel from the previous day (and from longer term storage).

The most significant rainfall which occurred during the period of study was on 18 September 1992 (37.7 mm at Wimborne St. Giles). This occurred during a relatively low flow period. Much of the sediment moved from the catchment surface on that occasion (as was evident in drains, across roads and trackways) may not have transported out of the catchment until the high flows, which did not exceed 1 ms^{-1} until December 1992.

Abstractions may have caused depletion of river flows in the Allen catchment (Newman 1991). It is possible that abstraction of water, from the Allen has an impact upon the conveyance of sediment from the catchment, by reducing flows below sediment transport entrainment thresholds and decreasing the capability of channelled flow to carry away materials delivered to the stream. This is particularly likely during summer flows which were down to less than 0.5 ms^{-1}. This possibility is worthy of further investigation. It is evident that, even without human interference, given the lagged impact of rainfalls upon streamflows and rainfall patterns like those of summer and autumn 1992, substantial channel storage of materials eroded from the catchment surface will occur.

The Chelmer yielded 13609 t y^{-1} in the 1992/1993 study period (71.6 t $km^{-2}y^{-1}$). This is, therefore, the study catchment with the highest suspended sediment yield per unit catchment area. It is also the most dominantly arable of the six catchments. There were observed to be many places within the catchment where tillage was seen to reach right up to the edges of watercourses. Although these soils are not considered the most vulnerable to surface erosion, many fields are ploughed straight downslope. There is considerable use of heavy machinery with many wheelings leading directly downslope and in close proximity to ditches. Although not unique to the Chelmer, these are all factors which are known to increase the likelihood of soil erosion and enhance delivery of sediments to rivers.

Overall, it is useful to compare these yields with other reported British yields. Walling and Webb (1987) have given a range of between 0-500 t km^{-2} yr^{-1} for localised research investigations with a value of 50 t km-2yr-1 as a typical suspended yield. Although the values found in the Chelmer were higher than this typical value, other study catchments did not have exceptional yields.

7. CONCLUSIONS

The field monitoring aspect of this study was badly affected by the exceptional dry conditions experienced over much of the study period. Hence, there were few opportunities for detailed monitoring of watercourses at times of high sediment mobility. The lack of soil erosion events meant that it was not possible to attain all the objectives of this research. This was particularly the case concerning the isolation of the magnitude and impacts of agricultural soil erosion from other sediment sources during the period of atypically low river sediment loads during this study.
However, the combination of wetter conditions, incorporation of data from other sources and extension of the field programme in 1992/1993, permitted some useful estimates of whole catchment outputs of sediment. In summary, the estimates indicate a range of yields from agricultural catchments ranging from 4 t km^{-2} y^{-1} for small upland grassland catchments, 25 t km^{-2} y^{-1} for large scale undisturbed grassland, through varying proportions of mixed grassland and arable, up to dominantly intensive arable yielding 71.6 t km^{-2} y^{-1}.

Another part of the field science involved short term deployment of samplers above and below an area of tillage with no undisturbed buffer between river and field. Monitoring of one flood event indicated that there was a significant supply of fine sediment to the River Severn, resulting in enhanced sediment outputs throughout the flood event, as opposed to the rapid, but relatively short-duration supply of material from the loose field surface material which had been anticipated. This behaviour suggests that where buffers are not present, supply of material from banks can be substantial even from short sections of ploughed stream sides, relative to reaches with well-vegetated banksides.

Forgoing the problems of conducting field research on soil erosion during a long period of dominantly dry weather, there is a growing body of British research which indicates that erosion rates have been enhanced by practices involved in arable cultivation, particularly during the last fifteen years. There is British and international case study evidence that sediment mobilised by agricultural soil erosion can be implicated in channel stability, water quality and habitat problems. Research is required to further elucidate the linkages between field erosion and within river channel impacts.

8. RECOMMENDATIONS

8.1 Improved monitoring

a) NRA does not currently monitor suspended solids at sufficient frequency or with sufficient spatial resolution to routinely pick up sediment pollution from non-point agricultural sources. This should be considered where potential for problems are perceived eg. in catchments with important fisheries where significant shifts to arable from permanent pasture are likely to occur.

b) Very few records of suspended sediment load can be obtained from existing NRA river sampling sites or archive records. To gain a further appreciation of the national impact of changes, in eg. land use, upon particulate loads, extension and co-ordination of the existing networks should be considered.

c) Intensive survey of river reaches, such as often occurs in ad hoc assessment of habitat for fish and other surveys, should incorporate more detail on bed sediments, with some quantitative baseline data on particle size characteristics. Bed sediment data particularly if repeated at regular intervals can give valuable clues and evidence for undesirable inputs of fine sediments from many sources.

8.2 Heightening perceptions of the "problem"

Very few of the NRA personnel contacted at the initiation of this project were aware of the potential for water quality or habitat problems associated with agricultural soil erosion, excepting a limited number who had taken an interest in the development of this area of scientific research or through personal experience had perceived links between, for example, increasing fine sediment deposition in reaches with important habitat for fisheries. Since this study began, several NRA regions have commissioned more localised studies concerned with specific rivers, indicating that perception of soil erosion problem is increasing.

A necessary focus was placed upon farm wastes in organic and solutional forms in the "Influence of Agriculture on the Quality of Natural Waters in England and Wales" (NRA, 1992). However, there is growing evidence of the importance that suspended solids, a significant source of which is field surfaces, is a major medium for the conveyance of nutrients and pesticides. It is therefore important that NRA officers should be aware of the soil types, locations, land uses and land use practices which are likely to increase the likelihood of soil erosion and inputs of sediment. They should also be aware that in addition to its physical impacts, this material is likely to contain enhanced nutrient or pesticide levels, relative to other sources (excepting some industrial and domestic effluents). There are also methods to prevent or reduce erosion and inputs to streams, such as adjustments to spatial patterns of crop cover, creation of riparian buffers and greater attention to the effects of heavy machinery such as soil compaction (leading to increased overland flows) and wheelings. These principles are described in a generalised form in the appendix and are based upon British and international experience.

There are many low cost ways to prevent particulate material from reaching watercourses and loss of soil is not in farmers interests. Therefore a positive attempt to educate farmers about reducing these risks would be worthwhile, perhaps with a leaflet conveying similar points to those made in the accompanying appendix which is intended as a stand alone document for this purpose.

8.3 Integrated research

This study has been focused upon seeking empirical evidence for increased sediment loads associated with agricultural practices which may enhance soil erosion. As illustrated by this research, there are great difficulties in acquiring data on the off-farm effects of soil erosion. It occurs very sporadically, both in time and space. It is dependent upon the coincidence of intense rainfall and particular land use practices, upon areas with specific hydrological, soil and topographic characteristics. Even where soil erosion does occur, delivery to streams is also highly variable. This makes assessment of the perceived problem of off-farm impacts very difficult at both regional and national scales.

There is a significant research community in the UK with interests in agricultural soil erosion and its off-farm impacts. To advance the NRA's aims of controlling pollution and the achievement of a progressive improvement in water quality, in the areas of both physical and chemical aspects of sediment pollution, it is in the NRA's interests to consider how future R&D could be targeted most effectively. A forum to explore, encourage and/or direct applied work in this field would be very worthwhile, possibly linked to existing buffer strip initiatives. Further linkage between groups who are looking at different parts of the system would be worthwhile. For example, integration of research by the Soil Survey on soil properties, erosion processes by Silsoe, Oxford, Wolverhampton and Cambridge Universities, further consideration of source labels, the delivery and downstream translation of eroded materials such as carried out by Exeter and Coventry Universities. More detailed consideration of the composition of the eroded sediment by Exeter University, the Institute of Freshwater Ecology and Institute of Hydrology (esp. particle size, nutrient and contaminant loadings) and further effort to produce integrated erosion, delivery and channel sediment transport modelling which perform well under British conditions would be timely.

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APPENDIX 1

GUIDANCE FOR FARMERS ON AGRICULTURAL SOIL EROSION

THE PROBLEM

Agricultural change and soil erosion

As agriculture has been changing over the last two decades, there has been increasing evidence of concern about losses due to soil erosion amongst the farming community. Results of an ADAS questionnaire has indicated that 17% of farmers thought that soil erosion had cost them money. In addition, a survey by MAFF, ADAS and Soil survey has indicated that in any one year up to 4% of fields may suffer erosion. In parts of England up to 40% of fields were found to be effected over a five year period. Some of the changes leading to increased vulnerability to soil erosion include:

- Extension of arable cultivation, at the expense of grassland which tends to be less easily erodible.

- Increased tillage during autumn and winter for cereals, leaving soils bare at times of highest rainfalls.

- Greater use of heavy machinery, which loosens surface soils, compacts subsurface layers and leaves wheel marks (wheelings). Compaction will prevent infiltration. This makes more of the rainfall run off across the field surface and presents the easily erodible loose surface materials for removal in the run off. Wheelings can concentrate flow, leading to rill and gully formation.

- Reduction in the organic content which binds the soil, therefore reducing resistance to erosion.

Adverse impacts for farmers

Movement of soil from fields to streams is bad news for farmers for many reasons. These include:

- Loss of the most productive layers of the soil.

- The finer and organic parts of the soil are removed preferentially, thereby reducing fertility and long term ability of the soil to retain water (particularly during periods of drought). Conversely, sand may also be selectively removed by erosion, thereby impeding free drainage of some soils.

- Reduction in the efficacy of fertiliser applications. For example, nitrate and phosphate will be eroded with the soil on to which it has been applied.

- Seedlings are removed with the soil, thereby reducing crop yield or requiring reseeding work.

- Eroded material can block or reduce efficiency of surface drains and ditches, necessitating expenditure on drain clearance.

Adverse impacts on rivers and streams

There are also many adverse impacts upon streams. These include:

- Deposition of fine sediment derived from field surfaces can cover the beds of streams, suffocating and blocking off light to the many animals and plants which live, or lay eggs, in river bed gravels.

- High concentrations of sediment in river waters may also effect fish health and survival.

- Sediments released from field surfaces may have high pesticide and nutrient contents which cause serious deterioration in stream water quality.

- Increased sediment loads can lead to increased shoaling, filling of pools, increased channel instability and reduction in stream gradients. This leads in turn to land drainage problems, loss of land by bank erosion and further stream sediment pollution problems.

SOLUTIONS

The National Rivers Authority and Farmers working together

Although the problem of soil erosion is serious, there are many ways in which it can be reduced. The main objective of both farmers and the NRA's are basically the same:

To keep the most important long term asset of the farm - fertile soil - on the farm and not transported away through streams and rivers, where it is a liability, ie. sediment pollution.

It is important to understand when soil is vulnerable to erosion and the routes by which it is most commonly transported off the farm to rivers as described below. The purpose of this appendix is also to recommend ways to protect soils from erosion on field surfaces, in close proximity to watercourses and through attention to drains and ditches. These recommendations are based on observed good practice by farmers, in addition to British and international scientific research.

Field surfaces

Soil type - Soil erosion can occur on all soil types. However, light loams and sandy soils are most vulnerable.

Tillage - This can be beneficial relative to no tillage systems. It is important to avoid concentration of runoff from rainfall across the soil surface. This may occur where soils are compacted or in wheelings formed during the movements of heavy plant. Try to avoid creating "tramlines", particularly of upslope/downslope orientation. Wheelings through the crop are desirable with as low gradients as possible, following as near to the contours of the field as you can without creating a vehicle stability safety hazard. Soils cultivated to a rough cloddy texture have a reduced vulnerability to erosion. Heavy rolling to flat smooth surface will increase the probability of soil erosion. Even where rolling and compaction is inevitable, it is worthwhile in large fields to consider the possibility of phasing tillage, eg. bottom half of field first, followed by the top half after the crop is established in the lower parts.

Crops - The type of crop, density and time of sowing are important as these influences the seasonal timing, height and extent of canopy cover. Most erosion occurs under cereals, without any crop and also potatoes, sugar beet and some market gardening cultivations. Greatest attention is required concerning winter cereal cultivation as the soil surface is left relatively bare for a long period at a time when growth is slowest and is subjected to the highest of the seasonal rainfalls. Under these circumstances areas of erosion tend to be at their most extensive and delivery of material to the stream is at its greatest. Crops tend to establish a protective canopy faster when cultivated in spring and although some high rainfalls occur in summer, areas of erosion tend to be less extensive and delivery to streams tends to be more limited. Therefore, on vulnerable soils growth of spring sown crops is preferable, leaving stubble as protection over the winter. Another possibility would be to introduce temporary grass into the arable rotation. This would reduce the period of vulnerability to soil erosion, thereby reducing long term soil erosion rates and increasing the organic content of the soil.

Riparian areas

It is obvious that not all the soil which is eroded in fields will reach watercourses. In the riparian zone, there is a much greater chance of this occurring than at greater distances away from a channel. For example, it may be 100 times more likely for soil to be lost to the stream, so particular care is required in this area. Great benefits are gained in terms of preventing soil loss by providing a vegetated margin ranging from a few metres up to 100 metres in width to encourage deposition of eroded sediments before they reach a stream. The vegetation, width, drainage, moisture retention and slope characteristics of this "buffer" are important factors in determining the most effective width. This might be determined in voluntary collaboration, without obligation, with the NRA. The creation of a shallow ridge eg. 10-20 cm., may also be sufficient to redirect and slow surface runoff which is itself often very shallow in depth.

Drains and ditches

Ditches and vehicle tracks which lead directly in to rivers should be avoided wherever possible and for this purpose the movement of heavy vehicles across streams should be minimised. The routing of drains towards floodplain depressions or constructed wetlands may be an effective trap for sediment, in addition to providing waste and nutrient control. The incorporation of silt traps into land drains is worthwhile, although this will not stop very fine sediment and will probably require repeated maintenance. In addition to the phasing of tillage within large fields, it would be worthwhile to consider revising field boundaries, to break long slopes up in to separate fields with boundary ditches designed to disperse flow. Ideally boundary ditches should have shallow gradients, be grass lined and capable of carrying the flow concentrated at field boundaries without in themselves being subject to erosion.