Provenance and Transfer of Fine Sediment in the Lugg Catchment, Herefordshire, UK

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ABSTRACT

An extensive fine sediment research monitoring programme, funded through the SITA Trust's 'Enriching Nature' programme, has been undertaken to evaluate the value of a catchment-wide, monitoring approach to establish spatial and temporal patterns and sources of fine sediment in the Herefordshire Lugg catchment. The aim of the project was to investigate the sources and patterns of fine sediment movement to help target management resources to reduce the impact of excessive siltation.

Continuous (15 minute) flow and suspended sediment concentrations were monitored at five sink sites between April 2009 and November 2012 to assess the spatio-temporal variations in suspended sediment. Episodic high suspended sediment concentrations in the Lugg catchment persistently exceeded 25 mg L^{-1} over the period of study. Delivery of suspended sediments to the sites was also monitored using time-integrated samplers. A sediment fingerprinting and mixture modelling procedure based on geochemical properties was utilised to identify key sub-catchments that persistently delivered fine sediment over the period of study. Sources of fine sediment were also identified and evaluated based on differing land use types in four of the main sub-catchments recognised as important contributors of sediment at the catchment scale. The sediment fingerprinting technique was refined to incorporate appropriate weighting and correction factors to improve the ability of the composite fingerprint to discriminate between source types.

The monitoring programme established the spatial and temporal characteristics of fine in-channel sediment and its sources within the wider catchment. Priority sub-catchment areas that posed the greatest risk of being fine sediment pollution sources were identified as the Cheaton Brook, Curl Brook, Ridgemoor Brook and Moor Brook. The sub-catchment scale sourcing results indicate that if siltation problems in the Lugg catchment are to be tackled effectively, catchment managers should target the reduction of fine sediment from farm track surfaces in the Cheaton, Curl and Moor Brook sub-catchments, while targeting the reduction of sediment mobilised from arable and pasture surfaces in the Ridgemoor Brook sub-catchment. This study has therefore assisted in strengthening the evidence of the sediment problem in the Herefordshire Lugg catchment and has provided an evidence base to aid catchment management to enable the implementation of mitigation measures in an effective targeted approach.

DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of the University of Gloucestershire and is original except where indicated by specific reference in the text. No part of the thesis has been submitted as part of any other academic award. The thesis has not been presented to any other education institution in the United Kingdom or overseas.

Any views expressed in the thesis are those of the author and in no way represent those of the University.

Signed …………………………………………….Date ………………………

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CHAPTER 1

INTRODUCTION

1.1 The Sediment Problem

Fine-grained sediment, defined as material <2 mm in size and encompassing sand (<2000 to >62 µm), silt (<62 to >4 µm) and clay (<4 µm), is a natural and integral component of river systems (Wood and Armitage, 1997; Owens *et al*., 2005; Jones *et al*., 2012; Vercruysse *et al.,* 2017). However, in recent years there has been increasing concern regarding elevated levels of fine sediment being delivered to and transported by rivers and streams. Anthropogenic activities and in particular land management practices such as agriculture (e.g. Collins and Walling, 2007a; Schriever *et al*., 2007; Withers *et al*., 2007; Boardman *et al*., 2009; Deasy *et al*., 2009; Jones and Schilling, 2011; Zhang *et al*., 2014; Collins *et al*., 2016; Naden *et al.,* 2016), forestry operations (e.g. Scrivener and Brownlee, 1989; Davies and Nelson, 1993; Grayson *et al.,* 1993; Madej *et al*., 2001; Motha *et al.,* 2003; Chappell *et al*., 2004; Croke *et al*., 2005; Ziegler *et al*., 2007; Negishi *et al*., 2008; Futter *et al*., 2016), construction (e.g. Cline *et al*., 1982; Myers *et al*., 1985; Davey *et al*., 1987; Angermeier *et al*., 2004; Lachance *et al*., 2008) and mining (e.g. Turnpenny and Williams, 1985; Davies-Colley *et al*., 1992; Brown *et al*., 1998) have greatly increased the natural sedimentation processes. The resulting accelerated rates of soil erosion have enhanced the supply and delivery of fine sediment to freshwater systems (Minella *et al.,* 2009).

The input of excessive quantities of fine sediment can have important hydrological, geomorphological and ecological implications, altering the physical and biological environment and causing lotic ecosystem degradation (Owens *et al*., 2005; Collins and Walling, 2007a; Owens *et al*., 2016; Laceby *et al*., 2017; Mathers *et al*., 2017). The transport of fine sediment in the water column increases turbidity and reduces light penetration, thereby reducing primary production and the availability of high quality habitat for benthic organisms (Wood and Armitage, 1997; Henley *et al*., 2000; Wilbur and Clarke, 2001; Collins *et al*., 2010b). Deposition of this sediment can smother river substrates, alter channel morphology and degrade aquatic habitats, particularly through the siltation of fish spawning gravels (Sear, 1993, Waters, 1995; Wood and Armitage, 1999; Acornley and Sear, 1999; Armstrong *et al*., 2003; Walling *et al*., 2003; Owens *et al*., 2005; Bilotta and Brazier, 2008; Minella *et al*., 2008; Kemp *et al*., 2011; Jones *et al*., 2012; Owens *et al*., 2016). The proportion of interstitial fine sediment, in particular, is critical for salmon embryo survival (Heywood and Walling 2007). Early laboratory studies suggested that where fine sediment (< 2 mm) exceeds 15 ± 5% of the channel bed material, salmonid embryo survival reduces to less than 50% (Milan *et al.,* 2000). However, more recent studies have further explored the physical characteristics of fine sediment and the associated effects on salmonids. Attention in the literature shifted to gravel permeability and oxygen supply rate as limiting factors for embryo survival. Fine sediment blocks the pores and reduces intragravel flow, preventing the sufficient supply of dissolved oxygen to the embryos (Walling *et al.,* 2003; Greig *et al.,* 2005). In addition, sand sized particles block interstitial pore spaces trapping finer grained particles and creating a barrier to alevin escape (Olsson and Persson, 1988).

Further studies have demonstrated that embryo survival is associated with grain size and oxygen supply rate. For example, Levasseur *et al.* (2006) concluded that very fine sediment (< 63 µm) was highly detrimental to embryo survival, whereas the larger sediment (up to 2 mm) had no corresponding effect. This has been supported through field studies which found that survival rates in spawning gravels were lower at sites dominated by silt and clay compared to sites with high levels of sand accumulation (Greig *et al*., 2007). Furthermore, Lapointe *et al*. (2005) and more recently Franssen *et al*. (2012) have demonstrated that the detrimental effects of silt and clay sized particles are amplified when combined with coarser sand-sized material by reducing pore sizes and leading to enhanced blocking by fines. In contrast, Louhi *et al*. (2011) reported that percentage survival of brown trout was not related to any specific absolute grain size. Similarly, Sear *et al*. (2016) did not find a significant relationship between specific size fraction and mortality. However, the experimental conditions of the latter studies differed in that local concentrations of clay within the egg baskets were much lower compared to other studies.

In addition to sediment quantity, contemporary research has demonstrated that the source of fine sediment also affects salmonid embryo mortality. For example, Sear *et al*. (2016) concluded that organic matter influences the supply of oxygen in spawning gravels and as a result the impact of fine sediment on embryo survival can be controlled by the organic matter content and oxygen consumption of the catchment source material.

Fine sediment also plays a significant role in the transfer and fate of nutrients, pesticides and other contaminants, including phosphorus (P), nitrogen (N), particulate organic carbon (POC) and trace or heavy metals (Kronvang *et al*., 1997; 2003; Warren *et al*., 2003; Collins *et al.,* 2005; Chalmers *et al*., 2007; Ballantine *et al*., 2008; Horowitz, 2008; Yakutina, 2011; Pavanelli and Selli, 2013; Yu *et al*., 2017). Nutrients and other contaminants derived from point sources such as effluent from industrial facilities and sewage treatment works (STWs) or from non-point sources such as rainfall generated runoff from roads and agricultural land (e.g. Edwards and Withers, 1998; Heathwaite and Dils, 2000; Owens *et al*., 2001; Hutchins *et al*., 2002; Deasy *et al*., 2008) are preferentially bound to particles of fine sediment (Quinton *et al*., 2001; Owens and Walling, 2002). These contaminants can subsequently be transported with suspended sediment or temporarily stored within the channel system (Owens *et al*., 2008). Elevated concentrations of these pollutants are capable of causing further deleterious impacts on water quality, such as eutrophication, and as a result can have important implications for river ecology (Foy and Withers, 1995; Heathwaite *et al*., 1996).

Sediment is therefore recognised as a major pollutant in freshwater aquatic environments and has subsequently received increasing attention from scientists, policy teams and catchment managers (Gellis and Walling, 2011; Collins *et al*., 2012a; Mukundan *et al*., 2012; Collins *et al.,* 2016; Collins and Zhang, 2016; Naden *et al.,* 2016; Mathers *et al*., 2017). Acknowledgment of the wide-ranging environmental significance of fine sediment accumulation has generated a need for improved information on suspended sediment loads transported by rivers and streams (Walling, 2005). Furthermore, a reliable understanding of the nature and relative contribution of different sediment sources and transport pathways is an essential requirement for assisting in the design and implementation of targeted management strategies to control and reduce sediment mobilisation (Owens *et al*., 2000; Collins and Walling, 2004; Collins *et al*., 2010a; 2016; 2017).

1.2 Land Use and Sources of Fine Sediment

The supply and delivery of fine sediment, leading to excessive interstitial sediment levels, has been associated with recent anthropogenic activities (Heaney *et al.,* 2001; Gilvear *et al.,* 2002; Collins and Zhang, 2016). Such activities include land use change, in particular, land management actions and agricultural practices (Johnes and Hodgkinson, 1998; Greig *et al.,* 2005; Sharma *et al.,* 2011; Zhang *et al*., 2014; Foucher *et al*., 2015; Alberto *et al.,* 2016; Collins *et al*., 2016; Le Gall *et al*., 2017; Schmidt *et al*., 2018). For example, the expansion of arable cultivation, focusing of livestock herds, removal of barriers to surface runoff connectivity, such as hedge or riparian buffers, and installation of field drains to aid field drainage can increase the supply of fine sediment from the catchment surface to the river network and sedimentation within gravel substrates used for spawning (Collins and Davison, 2009; Collins *et al.,* 2010a; 2012b). This is further supported by Schmidt *et al*. (2018) who reported that agricultural expansion doubled contemporary sediment yields in Chinese rivers from the background rate of sediment generation.

1.2.1 Sediment Sources from Agricultural Topsoils

Several studies have shown that intensive grazing systems are an important contributor to environmental degradation and water quality problems, especially in catchments where pasture dominates the landscape (Kurz *et al.,* 2006; Dewry *et al*., 2008; Collins *et al*., 2010a; 2012b). Walling and Collins (2005) reviewed the findings of 48 sediment sourcing studies across the UK and found that relative contributions resulting from the erosion of pasture and moorland surface soils ranged between 2 and 89%. The higher contributions were recorded for the north and west of the country where permanent grassland and moorland represent the dominant land use. For example, Walling *et al*. (1999) working in the Yorkshire Ouse catchment, England, concluded that estimated contributions from pasture topsoils were as high as 70 and 75% in two particular sub-catchments. In addition, Owens *et al.* (2000) suggested that contributions from pasture surface soils were 49% in one sub-catchment in the River Tweed, northern England. In the Severn catchment, western England/Wales, Collins *et al*. (1997a) found that pasture sources contributed between 40 and 89% of the suspended sediment. More recent studies have reported contributions from pasture topsoils ranging between 10 and 67% in the Somerset Levels (Collins *et al*., 2010b), between 11 and 92% in the River Axe catchment, Dorset (Collins *et al*., 2012b) and between 37 and 66% in the Tamar catchment, southwest England (Smith and Blake, 2014).

The corresponding relative contributions from surface erosion of cultivated fields in the review by Walling and Collins (2005) ranged between 1 and 78%, with the higher contributions being recorded for the mixed agriculture catchments in southern England where arable land is widespread. For example, two separate studies in the Culm catchment, southern England by Walling and Woodward (1995) and He and Owens (1995) estimated arable contributions to be 60% and 53% respectively. Collins *et al.* (2010b) concluded that mean relative contributions from eroding cultivated surface soils were as high as 57% in the Somerset Levels. In addition, Walling *et al.* (2008) working in a number of sub-catchments in the Hampshire Avon catchment, England, reported relative contributions from cultivated fields ranging from 33 to 78%. They found that this was the dominant source of suspended sediment in all but one of the sub-catchments. In the same study, arable contributions ranged from 20 to 56% in the Wye catchment, Wales. In contrast, contributions from this source type were estimated to be 3 and 9% in the Herefordshire Frome and Arrow catchment respectively (Collins *et al*., 2013a). Similarly, estimated contributions from arable topsoils ranged between 1 and 16% in the River Axe catchment, Dorset (Collins *et al*., 2012b) and between 1 and 19% in the River Piddle catchment, southwestern England (Collins *et al*., 2010c). Nevertheless, the review by Collins and Walling (2005) suggested that agricultural topsoils (cropping, pasture and moorland) and woodland surface soils typically account for ca. 85-95% of the suspended sediment load (Collins *et al*., 2010).

1.2.2 Sediment Sources from Channel Bank Erosion

According to the review of sediment sourcing data for England and Wales by Walling and Collins (2005), bank erosion contributions to suspended sediment flux range from <5% to >50%. The range of values suggested evidence of several controls. Catchment size appears to exert a significant influence on the magnitude of the contribution in that values for very small catchments are all relatively low. For example, this is evidenced in a study by Collins *et al.* (1997c) in the River Dart catchment, south west England, where the contribution from channel bank erosion was only estimated to be 5%. Similarly, channel bank contributions were estimated to be 8% in the Upper Avon catchment, south west England (Heywood, 2003). Collins *et al*. (2013) also reported average median channel bank contributions of 3 and 7% in the Herefordshire Frome and Arrow catchments respectively, whereas mean channel bank contributions of 22% have been reported in the River Axe catchment (Collins *et al*., 2012b). Equally, there is a clear trend for channel bank sources to assume greater relative importance as a sediment source in the northern and western areas of the country, where contributions in excess of 30% are common. For example, Owens *et al*. (2000) concluded that channel bank contributions were as high as 48% in the River Tweed catchment, England. Likewise, Walling *et al.* (1999) working in the Yorkshire Ouse catchment, England suggested that estimated channel bank contributions were 37%. In addition, contributions from this source type were estimated to range between 22 and 63% in the Tamar catchment (Smith and Blake, 2014). Despite these high contributions reported in certain catchments, the review by Walling and Collins (2005) suggested that eroding channel banks typically account for ca. 5-15% of the suspended sediment load of rivers in the UK.

1.2.3 Sediment Sources from Road and Farm Track Surfaces

In the UK, most research on road sediment has been undertaken in urban settings. For example, Ellis *et al*., (1987) and Ellis (1999) suggested that highways may account for up to 50% of the total suspended sediment load in urban catchments. Lawler *et al*., (2006) working in the urban upper Tame catchment in the West Midlands, England, concluded that the road network was important as a distal source of sediment. Alternative work in the UK has focused upon the impacts of roads in forested catchments. For example, Carling *et al.,* (2001) noted several important issues in relation to sediment pressures from forest roads. Issues included erosion of road-cuts prior to vegetation growth, watercourse crossings and the need for appropriate culvert design and direct rutting and erosion due to direct traffic pressures (Collins *et al.,* 2010).

More recent studies have focused on the contribution of fine sediment from damaged road verges, which represent an important source of fine sediment, particularly in rural catchments. The ongoing Catchment Sensitive Farming (CSF) initiative has been a big driver in identifying the contribution of sediment from damaged road verges in catchments with fine sediment issues. Road verges can get damaged and eroded by a range of vehicles and regular livestock movements, causing the removal of protective vegetation cover and the loosening of soil particles. Modern farm machinery is frequently too wide for narrow rural roads, resulting in the erosion and undercutting of verges. Delivery of sediment mobilised from damaged road verges is promoted by the high connectivity to river channels due to road drainage systems and surface runoff entry points beside bridges and at stream crossings and fords (Collins *et al*., 2010). For example, Collins *et al*. (2012b) estimated mean sediment contributions from damaged road verges to be as high as 37%, in the River Axe catchment, southern England. Similarly, a more recent study in this catchment looking at sediment-associated organic matter sources reported contributions from this source type to range between 4 and 35% (Collins *et al*., 2017b). Furthermore, other studies concluded that overall mean sediment contributions from damaged road verges were 33% in the Hampshire Avon catchment, England (Collins *et al*., 2010) and 48% in the River Rede catchment, northern England (Collins *et al.,* 2014). In contrast, mean sediment contributions from damaged road verges in the River Arrow catchment, Herefordshire (Collins *et al*., 2013a) and the Somerset Levels (Collins *et al*., 2010b) were estimated to be 4% and 12% respectively. Similarly, sediment contributions from this source type were estimated to be 11 and 15% in the River Ithon and Lugg catchments respectively (Collins *et al.,* 2014). Furthermore, Zhang *et al*. (2017) reported that damaged road verges were an insignificant source of sediment in the River Itchen catchment, Hampshire, with contributions ranging between 2 and 6%.

Unsealed roads and tracks have been found to have a significant impact on sediment mobilisation and water quality (Anderson and MacDonald, 1998; Sheridan *et al*., 2008). Eroding farm tracks act as concentrated flow paths for the efficient delivery of material mobilised from surface sources (Edwards and Withers, 2008; MacDonald and Coe, 2008, Collins *et al.,* 2010c). Collins *et al*. (2012a) reported that fine grained sediment contributions from farm track surfaces ranged from 45 to 73% in the agricultural River Kennett catchment, Southern England. Collins *et al.* (2010c) also suggested that through visual observations during storm events farm tracks delivered ca. 90% of the sediment mobilised from agricultural land in the River Piddle catchment, UK.

1.3 Policy and Management

Controlling excessive inputs of fine sediment to water bodies represents a major policy challenge in many countries (Collins *et al*., 2016). A key policy driver for diffuse water pollution is the EU Water Framework Directive (WFD) (2000/60/EC), which came into effect in 2003, establishing a framework for the protection of European waters (European Commission, 2000). It requires all inland and coastal waters to achieve “good status” by 2015 through a catchment-based system of River Basin Management Plans (RBMPs) which are reviewed and updated every six years. Where this was not possible, all WFD objectives must be achieved by the end of the second and third management cycles which extend from 2015 to 2021 and 2021 to 2027 respectively (European Commission, 2012). Other key policy drivers for diffuse water pollution include the Habitats Directive (92/43/EEC) and the Freshwater Fish Directive (78/659/EEC, later repealed by 2006/44/EC), although the latter was revoked in December 2013 as part of the WFD (European Commission, 2013).

In England and Wales, the WFD is implemented through the Water Environment (Water Framework Directive) (England and Wales) Regulations 2017 (S.I. 2017/407) which sets out the provisions of the directive so that all environmental objectives and requirements are fully reflected in legislation. In 2015, only 17% of surface water bodies in England were classified as being in good or high ecological status. As a result, an extension to meet the WFD objectives was invoked with the Environment Agency citing technical infeasibility, disproportionate costs and slow recovery times for the failure to meet the WFD objectives (Environment Agency, 2015). The second set of RBMPs were established in 2015 with 75% of surface water bodies in England having an objective of reaching good ecological status. However, it is predicted that compliance with the WFD will have risen to just 21% by the end of the second management cycle (Environment Agency, 2015). Furthermore, a recent report on the state of the environment revealed that 86% of rivers in England fail to meet standards for good ecological status, citing agriculture and rural land management, the water industry and urban and transport pressures as the main reasons for the failure (Environment Agency, 2018). Similarly, the results from the first RBMPs indicated that more than half of the water bodies in Europe failed the WFD objective of achieving good ecological status (European Environment Agency, 2015). Therefore, the WFD has yet to deliver its main objectives of non-deterioration of waterbody status and the achievement of good ecological status for all EU waters (Voulvoulis *et al*., 2017).

In order to support the main objectives of the WFD, a characterisation of key pollutant pressures and associated impacts is essential in order to tackle diffuse pollution (Collins and Anthony, 2008). Furthermore, monitoring and the need for management is required to assess the current state of water bodies and to establish appropriate water quality targets (Voulvoulis *et al*., 2017). Modelled evidence for sediment policy support suggests that between 72 and 76% of the total sediment load delivered to all watercourses across England and Wales is attributed to the agricultural sector (Collins *et al*., 2009; Zhang *et al*., 2014). Given the widespread concerns about fine sediment pollution, the Catchment Sensitive Farming (CSF) Initiative was launched in April 2006 to deliver targeted advice to stakeholders on reducing diffuse water pollution from agriculture in a number of targeted catchments across England (Collins and Anthony, 2008). The scheme is currently in Phase 4 (2016-2021) after three previous Phases (running through to 2008, 2011 and 2016 respectively). It focuses upon the delivery of support and evidence-based advice delivered by a network of Catchment Sensitive Farming Officers (CSFOs), as opposed to regulation. However, it has been reported that voluntary action by farmers alone would not solve the problem of agricultural pollution. For example, the evaluation of CSF after Phases 1 and 2 (Environment Agency, 2011) and a more recent analysis during Phase 3 (Environment Agency, 2015) found that the scheme had only been effective at maintaining the status quo of sediment and nutrient concentrations. Furthermore, this approach lacks a scientific evidence base able to identify the major sources and transport pathways of suspended sediment on which to target remediation (Collins *et al.,* 1998). Therefore, in order to identify the relative contributions of different farm pollution sources and the most effective pollution mitigation measures, and to quantify the potential environmental outcome targets for each WFD management catchment (Environment Agency, 2017), CSF needs to assemble a multi-source evidence base with respect to the sources of sediment pollution (Collins *et al.,* 2010d).

As the WFD requires mitigation strategies to be introduced to tackle diffuse pollution, there is a need to adopt a catchment-wide perspective in developing sediment management plans (Collins *et al*., 2012a). However, there has been a lack of suitable monitoring strategies within the demanding timeframe of the WFD implementation (Dworak *et al.,* 2005). As a result, catchment managers have experienced difficulty in knowing where to target resources effectively and efficiently. It is not cost or time-effective to implement resources to manage the sediment problem across the whole catchment. Therefore, it is important for practitioners and policy makers concerned with these excessive sedimentation issues, to obtain reliable information on the key sources of the sediment pollution to efficiently target management options (Collins *et al.,* 2010a; 2017).

1.4 Approaches to Catchment Sediment Source Identification

Given that accelerated sediment delivery is associated with recent land use changes, particularly agricultural intensification (Naismith *et al*., 1996; Theurer *et al.,* 1998; Walling and Amos, 1999; Heaney *et al.,* 2001; Johnes *et al*., 2007; Zhang *et al.,* 2014; Schmidt *et al*., 2018), and siltation is widely accepted as a major contributing factor to the degradation of spawning habitat (Wood and Armitage, 1997; Acornley and Sear, 1999; Soulsby *et al.,* 2001; Greig *et al.,* 2005; 2007; Kemp *et al*., 2011; Sear *et al*., 2016), it is important to assemble meaningful information on the sources of fine sediment in order to develop effective management strategies and control policies to satisfy current legislative requirements. Fine sediment transported by a river represents a mixture of sediment derived from different locations and various types of sediment source within the catchment (Walling *et al*., 1999b). As a result, a relatively small area of the catchment, underlain by particular geology, or supporting a certain land use, could contribute most of the suspended sediment load (Walling, 2005). The quantification of sediment provenance within a catchment, so that available resources can be targeted at specific sources, is therefore an important element in the investigations of fluvial suspended sediment delivery (Collins and Walling, 2002; Collins *et al*., 2017). However, as sources of fine sediment are spatially and temporally variable in response to the complex interactions between processes influencing sediment mobilisation and delivery, the provision of reliable information on both the nature and importance of sediment sources within a catchment is extremely challenging (Collins and Walling, 2004).

1.4.1 Traditional Methods

Traditionally, methods for assessing the relative importance of sediment contributions from individual source types used a range of indirect measurement and monitoring techniques. A variety of techniques, which involve measurements of erosion activity or visual observations which are subsequently used to infer the relative importance of different potential sources (Walling, 2005), have been used. These include (i) assessments of sediment origin from sediment source maps (Skrodzki, 1972; Lao and Coote, 1993) to relate spatial distribution of erosion to physiographic, ecological and anthropogenic controls (Morgan, 1995); (ii) visual appraisals of potential sources from aerial photographs or field observations (Werrity and Ferguson, 1980; Wilson *et al.,* 1993) in order to provide evidence of the occurrence of channel bank and gully erosion (Barker *et al*., 1997; Eriksson *et al*., 2003); (iii) the monitoring or surveying of possible sources with profilometers (McCool *et al*., 1981; Shakesby, 1993), cross-profiling (Steegen *et al.,* 2000) and erosion pins (Davis and Gregory, 1994; Couper *et al*., 2002) to record the rate of surface lowering or retreat of features such as eroding channel banks (Lawler, 1993; Lawler *et al*., 1999; Stott, 1999); and (iv) the measurement of soil loss using erosion plots from areas supporting different land use (Thomas *et al*., 1981; Loughran *et al*., 1992).

However, the application of these indirect techniques is often limited by operational and economic constraints and a range of spatial and temporal sampling difficulties (Peart and Walling, 1988; Loughran, 1989; Walling *et al*., 1993; Loughran and Campbell, 1995; Collins and Walling, 2002). In addition, they only provide information on sediment mobilisation and are incapable of taking into account the efficiency of sediment delivery (Walling, 2005). As a result, linking potential suspended sediment sources to the channel network is limited, thus assumptions on the likely sources are frequently required, which may not be evident in some catchments (Loughran and Campbell, 1995).

Alternative approaches have used models and prediction procedures to infer sediment source contributions. For example, the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and its principle derivatives, the Revised Universal Soil Loss Equation (RUSLE) (Renard and Ferreira, 1993) and the Modified Universal Soil Loss Equation (USLE-M) (Kinnell and Risse, 1998) have been used to estimate average annual soil loss per unit land area (Nyakatawa *et al.,* 2001; Angima *et al*., 2003; Di Stefano *et al*., 2016). The input variables required in all forms of this erosion model include rainfall erosivity (the ability of rainfall to cause erosion), an estimate of soil erodibility (the vulnerability of the soils to detachment and transport), land cover information (crop erosivity factor), topographic information (slope length and gradient factors) and erosion control and management practice information (soil control factor). More recently, the use of this soil erosion model has been integrated with GIS-based procedures to predict soil losses and planning control practices in agricultural watersheds (Fistikoglu and Harmancioglu, 2002; Erdogan *et al*., 2007; Kouli *et al*., 2009; Biswas and Pani, 2015; Ganasri and Ramesh, 2016). However, these soil erosion models are not event-based and therefore cannot identify those events most likely to result in large scale erosion (Merritt *et al.,* 2003). The European Soil Erosion Model (EUROSEM) (Morgan *et al*., 1998) addresses this limitation by predicting event-based runoff and sediment discharge for different environmental conditions. Input variables used in this model include rainfall, infiltration, soil surface condition (surface roughness), surface runoff processes (flow velocity), soil detachment by raindrop impact and by runoff and transport capacity of the flow. The model computes soil loss as a sediment discharge defined as the product of the rate of runoff and the sediment concentration in the flow to give a volume of sediment passing a given point in time (Morgan *et al*., 1998; Smets *et al.,* 2011).

Furthermore, soil erosion models have an inherent inability to provide information on the fate of sediment once it is eroded. As a result, they have frequently been incorporated in other models, like for example, the spatially distributed soil erosion and sediment delivery model (WATEM/SEDEM) (Van Oost *et al.,* 2000; Van Rompaey *et al.,* 2001; Verstraeten *et al*., 2002). The WATEM/SEDEM model estimates the spatial patterns of soil loss and sediment flow across land units and has been applied at small catchment, watershed and regional scales under a wide range of environmental conditions (e.g. Van Rompaey *et al.,* 2005; Verstraeten *et al*., 2006; 2007; Verstraeten and Prosser, 2008; Krasa *et al.,* 2010; Alatorre *et al.,* 2012; Bezak *et al.,* 2015; Liu and Fu, 2016). It uses an adapted version of the RUSLE to calculate soil loss related to water erosion. The topographic input variable of the RUSLE model is adjusted by replacing slope length with the unit contributing area to account for a two-dimensional landscape. In addition, the model calculates the mean annual transport capacity using a transport capacity coefficient and an assessment of the potential for rill erosion and uses a routing algorithm to transfer the eroded sediment from the source to the river network.

Nevertheless, like with the more traditional techniques, these alternative approaches require assumptions to be made on sediment provenance and the associated effects on catchment sediment output. Furthermore, such studies do not offer continuous long-term information on catchment suspended sediment sources and therefore their ability to consider the effects of changing land use on sediment provenance is severely restricted (Collins *et al*., 1997b; Collins and Walling, 2004).

1.4.2 Sediment Fingerprinting Technique

In response to the problems associated with traditional monitoring and measurement techniques, sediment fingerprinting has attracted increasing attention as a reliable direct means of establishing catchment sediment sources (Peart and Walling, 1988; Walling and Woodward, 1995; Collins *et al*., 1997a;

1998; Walling and Collins, 2000; Walling, 2013; Owens *et al*., 2016; Collins *et al*., 2017; Pulley *et al*., 2017). The sediment fingerprinting technique is founded upon the assumption that various potential sediment sources can be discriminated by a number of different diagnostic physical and chemical properties. By using modelling techniques to compare these properties with those of suspended sediment, the relative importance of each individual source can then be determined (Peart and Walling, 1986; Walling and Woodward, 1992; Walling *et al*., 1993; 1999b). Early examples of this fingerprinting approach used mineralogical (Klages and Hsieh, 1975), geochemical (Wall and Wilding, 1976) and mineral magnetic (Oldfield *et al.,* 1979; Walling *et al*., 1979) properties to discriminate potential sources and to establish the likely source of suspended sediment. However, the scope of these studies was limited as they only offered a broad discrimination between a small number of potential sources, typically defined as either surface or subsurface material. Furthermore, they provided a simple qualitative assessment of the likely importance of particular sources (Walling, 2005; Mukundan *et al*., 2012).

As the potential shown by these early studies has been further explored, the sediment fingerprinting approach has been developed and refined to include an expanded range of chemical, physical and biological properties in order to improve the discrimination between several potential sediment sources (Du and Walling, 2017). Chemical properties include clay mineralogy and mineral-magnetism (Caitcheon, 1993; Walden *et al*., 1997; Slattery *et al*., 2000; Gingele and De Deckker, 2005; Zhang *et al*., 2008; Hatfield and Maher, 2009), geochemistry (Collins and Walling, 2002), fallout radionuclides (Walling and Woodward, 1992; Olley *et al*., 1993; He and Owens, 1995; Wallbrink *et al*., 1996; 1998; 1999; Wilkinson *et al.,* 2013; Belmont *et al*., 2014; Evrard *et al*., 2016) isotopic signatures (Douglas *et al.,* 1995; Fox and Papanicolaou, 2007; Yang *et al*., 2008) and biomarkers (Hancock and Revill, 2013; Alewell *et al*., 2016; Reiffarth *et al*., 2016). Physical properties include colour (Grimshaw and Lewin, 1980; Krein *et al*., 2003; Martínez-Carreras *et al*., 2010b; Barthod *et al.,* 2015; Pulley *et al.,* 2018) and grain size (Weltje, 2012). Biological properties include soil enzymes and pollen (Brown, 1985; Papanicolaou *et al*., 2003).

Owing to the spatial variability of source materials and the complexity of the sediment routing and delivery process within a river catchment, along with the requirement to discriminate between various potential sources, the use of single-component fingerprints is inadequate to establish the relative importance of potential sediment sources (Walling *et al.,* 1999b; Walling and Collins, 2000; Collins *et al*., 2017). In addition, the ability to provide robust quantitative results and the reliability of this approach is likely to be compromised by spurious source-sediment matches (Molinaroli *et al*., 1991; Walling *et al.,* 1993). For example, although the concentration of an individual fingerprint property could resemble a particular source, it might also represent a mixture of various other sources within the catchment. Subsequently, it has been recognised that the discrimination of catchment sediment sources can be significantly enhanced by using multiple diagnostic properties from a particular subset or from several property subsets in combination (Walling *et al*., 1993; Devereux *et al.,* 2010). By testing the discrimination of potential sediment sources within a number of contrasting catchments, Collins and Walling, (2002) reported that multi-component fingerprints incorporating constituents from several groups of properties, consistently provided a more effective means of differentiating source samples. Therefore, the use of such composite fingerprints permits a greater number of potential sources to be identified and a more reliable means of establishing sediment provenance.

The source fingerprinting technique has been successfully used in many studies to provide detailed information on the sources of suspended sediment (e.g. Murray *et al*., 1993; Slattery *et al.,* 1995; Collins *et al*., 1997c; Kronvang *et al*., 1997; Wallbrink *et al*., 1998; Walling *et al*., 1999b; Owens *et al*., 2000; Collins *et al*., 2001; Russell *et al*., 2001; Carter *et al*., 2003; Gruszowski *et al*., 2003; Motha *et al*., 2003; 2004; Minella *et al*., 2008; Walling *et al*., 2008; Wilson *et al*., 2008; Banks *et al*., 2010; Collins *et al.,* 2010c; Devereux *et al.,* 2010; Martínez-Carreras *et al*., 2010b; Mukundan *et al*., 2010; Blake *et al*., 2012; Smith and Blake, 2013; Barthod *et al*., 2015; Theuring *et al*., 2015; Bainbridge *et al.,* 2016; Vale *et al.,* 2016; Lui *et al*., 2017; Rowntree *et al*., 2017; Tiecher *et al*., 2018). The same approach can also be applied to fine matrix sediment accumulating in spawning gravels (e.g. Krause *et al*., 2003; Walling *et al*., 2003; Collins and Walling, 2007; Collins *et al*., 2010a; 2012b; 2013; Gellis *et al*., 2017; Le Gall *et* *al.,* 2017; Zhang *et al*., 2017), and overbank floodplain deposits (e.g. Walling *et al*., 1997; Botrill *et al*., 2000; Collins *et al*., 2010b; Franz *et al*., 2014; Monjoro *et al.,* 2017) to determine contemporary sediment provenance. In addition, the technique has been employed to estimate changes in the sources of longer-term sediment deposits from river floodplain, lake and reservoir cores (e.g. Foster and Walling, 1994; Collins *et al*., 1997d; Owens *et al*., 1999; Rowan *et al*., 1999; Owens and Walling, 2002; Foster *et al*., 2003; Foucher *et al.,* 2015; Kraushaar *et al.,* 2015; Laceby *et al*., 2015a; Pulley *et al*., 2015).

1.4.3 Classifying Potential Sources

As the scope of the fingerprinting technique has improved and the array of different fingerprint properties has increased, the range of potential sources that can be considered has been enhanced (Mukundan *et al*., 2012; Collins *et al*., 2017a). Potential sediment sources within a catchment can be divided into categories to distinguish the precise types of source or to determine the spatial provenance of transported sediment. Individual source types can be categorised in terms of surface soils under different land use and channel banks, or more simply as surface and subsurface sources. Alternatively, spatial provenance can be characterised on the basis of sediment contributions from individual tributary sub-catchments or distinct geological sub-areas (Figure 1.1).

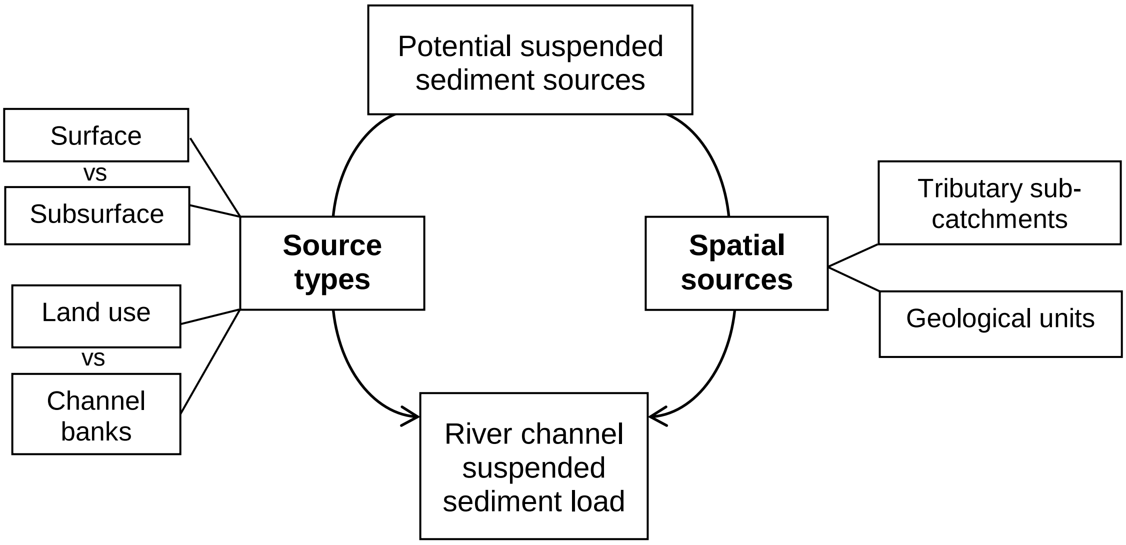

Figure 1.1 Classification of potential catchment sediment sources (adapted from Collins and Walling, 2004).

The source classification and the different components of the source categories will be determined by the major erosive processes present in specific catchments (Collins and Walling, 2004). Previous sediment fingerprinting studies have been predominantly concerned with distinguishing individual source types within spatially-constrained catchments. Whereas many early studies have only focused on a simple distinction between surface and subsurface sources (e.g. Peart, 1995; Kronvang *et al*., 1997), recent research has progressed to incorporate as many as five potential sources from areas of different land use and land use management practices. These include channel banks (Minella *et al.,* 2008; Lamba *et al*., 2017; Pulley *et al.,* 2017), topsoil from cultivated and pasture agricultural areas (Collins and Walling, 2007; Walling *et al*., 2008; Kraushaar *et al*., 2015; Tiecher *et al.,* 2018), subsurface sources from field drains (Russell *et al.,* 2001; Chapman *et al*., 2005), unmetalled roads and farm tracks (Gruszowski *et al.,* 2003; Motha *et al*., 2004; Collins *et al*., 2010c; 2012a), surface soils from woodland and forested areas (Motha *et al*., 2003; 2014; Lui *et al.,* 2016), damaged road verges (Collins *et al*., 2010d; Zhang *et al*., 2017), construction sites (Gellis *et al.,* 2009) and urban sources such as solids from sewage treatment works (STWs) and road dust (Collins *et al.,* 2010b; 2012a; Pulley *et al*., 2015). However, in larger catchments, where the number and spatial complexity of sediment sources is substantial, source fingerprinting studies have concentrated more on determining the spatial provenance of sediment at the catchment scale (Collins *et al*., 1997a; Collins and Walling, 2004; Theuring *et al*., 2015; Bainbridge *et al*., 2016). By dividing large catchments up into distinct spatial units, based on geological sub-areas, sub-basin types or tributary sub-catchments, the issues associated with the spatial complexities of individual source types are avoided. Nevertheless, the source ascription offered by this approach is typically basic and the succeeding interpretation, especially in the context of catchment management, is therefore difficult (Collins *et al*., 1997a). As a result, estimates of spatial provenance at the catchment scale should be integrated with the assessment of precise source types at the smaller sub-catchment scale to provide more comprehensive information on sediment sources. This will enable the fingerprinting technique to be successfully used as a research tool in sediment provenance investigations and to facilitate the implementation of targeted mitigation measures.

A review of previous sediment fingerprinting studies is presented in Table 1.1, detailing the particular source classification procedures adopted.

Table 1.1 Previous sediment fingerprinting studies.

Reference	**Catchment**	**Classification**
	Individual source types	
Banks *et al*. (2010)	Mill Stream Branch, USA	Arable, forests and channel banks
Blake *et al*. (2012)	Furze Brook (River Otter), UK	Arable (maize and winter wheat), pasture, woodland and channel banks
Collins *et al.* (1997b)	Plynlimon (Upper Severn), UK	Forest, pasture and channel banks
Collins *et al*. (1997c)	Dart (River Exe); Plynlimon (Severn), UK	Arable, pasture, woodland and channel banks
Collins *et al*., (2001)	Upper Kaleya, Zambia, Africa	Arable (communal and commercial), pasture and channel banks
Collins *et al*. (2010a)	Selection of rivers in South West, UK	Surface and channel bank / subsurface sources
Collins *et al*. (2010c)	River Piddle, UK	Arable, pasture, farm track surfaces and channel banks
Collins *et al*. (2010d)	River Avon, UK	Road verges and channel banks
Collins *et al*. (2012a)	River Kennet (Thames), UK	Agricultural topsoils, farm tracks, road verges, street dust and channel banks
Collins *et al*. (2013)	River Blackwater, UK	Instream decaying vegetation, road verges, septic tanks, farm yard manure
Collins and Walling, (2007)	River Frome and River Piddle, UK	Arable, pasture, woodland and channel banks
Evans *et al*. (2006)	Bush catchment, Northern Ireland	Arable, forestry logging, drainage maintenance and channel banks
Foucher *et al*. (2015)	Louroux Pond Catchment, France	Surface (cropland) and subsurface (channel bank) sources
Franz *et al*. (2014)	Lago Paranoá, Brazil	Urban, agricultural and natural sources
Gellis *et al.* (2009)	Chesapeake Bay, USA	Arable, forests and channel banks
Gellis *et al.* (2017)	Watersheds in Midwest USA	Upland surface and channel sources
Gruszowski *et al*. (2003)	River Leadon (Severn), UK	Arable, pasture, roads, subsoil and channel banks
Hatfield and Maher, (2009)	Bassenthwaite catchment, UK	Surface and subsurface sources
He and Owens, (1995)	River Culm (Exe), UK	Arable, pasture and channel banks
Krause *et al*. (2003)	Williams River, Australia	Pasture, un-surfaced roads and channel banks
Kraushaar *et al.* (2015)	Wadi Al-Arab Catchment, Jordan	Orchards, arable and pasture topsoils and geological subsurface sources
Kronvang *et al*. (1997)	Gelbæk Stream, Denmark	Surface and subsurface sources
Laceby *et al.* (2015a)	Baroon Pocket Reservoir, Australia	Geological sources
Laceby *et al*. (2015b)	Moreton Bay, Australia	Subsurface sediment sources
Lamba *et al.* (2015)	Pleasant Valley, Wisconsin, USA	Agriculture, woodland and channel banks
Lui *et al*. (2016)	Bull Creek Watershed, USA	Arable and rangeland (woodland) sources

Table 1.1 (*cont*) Previous sediment fingerprinting studies.

Lui *et al*. (2017)	Little Bow River, Alberta, Canada	Upstream sources, irrigation flow channels, agricultural land and stream banks
Manjoro *et al.* (2017)	Mgwalana catchment, Eastern Cape, South Africa	Surface and subsurface sources
Martínez-Carreras *et al.* (2010b)	Attert River, Luxembourg	Topsoil (arable, pasture, forest), unmetalled roads and channel banks
Minella *et al*. (2008)	Arvorezinha catchment, Brazil	Arable, unpaved roads and channel banks
Motha *et al.* (2003)	West Tarago, Australia	Forests, arable and surfaced / un-surfaced roads
Motha *et al.* (2004)	East Tarago, Australia	Arable, forests, roads and grouped lands (pasture, arable, un-surfaced roads)
Mukundan *et al*. (2010)	North Fork Broad River, USA	Arable, pasture, forests, roads, construction sites, channel banks
Nagle *et al*. (2007)	Finger Lakes and Catshill region, USA	Cultivated topsoil and channel banks
Papanicolaou *et al.* (2003)	Upper Palouse River, USA	Forest and agricultural topsoils
Peart, (1995)	Lam Tsuen River, Hong Kong	Surface and subsurface sources
Peart and Walling, (1986)	Jackmoor Brook (River Exe), UK	Arable, pasture and channel banks
Pulley *et al.* (2015)	River Nene Basin, East Midlands, UK	Channel banks, agricultural topsoils and urban street dust
Pulley *et al.* (2017)	River Nene Basin, East Midlands, UK	Surface (topsoil) subsurface (channel bank) sources
Russell *et al*. (2001)	Rosemaund and Smisby catchments, UK	Surface sources, field drains and channel banks
Slattery *et al*. (1995)	Stour catchment, UK	Surface soil and channel banks
Smith and Blake, (2013)	River Tamar, UK	Arable, pasture and channel banks
Smith and Dragovich, (2008)	Lachlan River, Australia	Surface and subsurface sources
Thompson *et al*. (2013)	Down and Louth catchments, Ireland	Arable, pasture, woodland and channel banks
Tiecher *et al.* (2018)	Conceição River, Brazil	Cropland, un-paved roads and channel banks
Vale *et al*. (2016)	Manawater River, New Zealand	Geological surface and subsurface sources
Wallbrink *et al*. (1996)	Murrumbidgee River, Australia	Surface and subsurface (channel bank and gullies) sources
Wallbrink *et al*. (1998)	Murrumbidgee catchment, Australia	Arable, pasture and channel banks
Wallbrink *et al*. (2003)	Bundella Creek, Australia	Arable, pasture, woodland and subsoil from gullies and channel banks
Walling *et al*. (1993)	River Dart and Jackmoor Brook (Exe), UK	Arable, pasture and channel banks
Walling *et al*. (2003)	Selection of rivers in England and Wales	Surface and subsurface sources
Walling *et al*. (2008)	Avon and Wye sub-catchments, UK	Arable, pasture, woodland and channel banks
Walling and Woodward, (1992)	River Dart and Jackmoor Brook (Exe), UK	Arable, pasture, woodland and channel banks

Table 1.1 (*cont*) Previous sediment fingerprinting studies.

Wilson *et al.* (2008)	Selection of catchments in USA	Eroded surface soils and channel banks
Zhang *et al.* (2017)	River Itchen, Hampshire, UK	Catchment based (farmyard manures, road verges, septic tanks) and channel based (instream vegetation, fish and watercress farms) sources
Spatially defined sources		
Bainbridge *et al*. (2016)	Burdekin River Catchment, Australia	Geological sub-areas
Bottrill *et al*. (2000)	River Severn, UK	Tributary sub-catchments and geological sub-areas
Caitcheon, (1993)	Ord River (Murrumbidgee), Australia	Tributary sub-catchments
Chapman *et al.* (2005)	Rosemaund and Smisby catchments, UK	Soil type
Collins *et al.* (1996)	River Exe and River Severn, UK	Tributary sub-catchments
Collins *et al.* (1997d)	River Exe and River Severn, UK	Geological sub-areas
Collins *et al.* (1998)	River Exe and River Severn, UK	Geological sub-areas
Le Gall *et al.* (2017)	Guaporé catchment, Brazil	Soil type
Nosrati *et al.* (2018)	Mirabad Drainage Basin, Iran	Sub-basins
Owens *et al*. (1999)	River Ouse, UK	Geological sub-areas
Rowntree *et al.* (2017)	Vuvu River, Mzimbubu River, South Africa	Geological sub-areas
Theuring *et al*. (2015)	Kharaa River Basin, Mongolia	Tributary sub-catchments
Integration of spatial provenance and source type assessment		
Barthod *et al*. (2015)	South Tobacco Creek, Manitoba, Canada	Sub-basin (headwaters and outlet); topsoil, streambank and shale sources
Carter *et al*. (2003)	River Aire and River Calder (Ouse), UK	Geological sub-areas; arable, pasture, woodland, STWs, road dust, channel banks
Collins *et al*. (1997a)	River Exe and River Severn, UK	Sub-basin types; arable, pasture, woodland and channel banks
Collins *et al*. (2010b)	River Parrett and River Brue, UK	Tributary sub-catchments; arable, pasture, road verges, STWs and channel banks
Collins *et al*. (2012b)	River Axe, UK	Tributary sub-catchments; arable, pasture, road verges and channel banks
Koiter *et al.* (2013a)	South Tobacco Creek, Manitoba, Canada	Topsoil, streambank and shale sources
Owens *et al.* (2000)	River Tweed, UK	Geological sub-areas; arable, pasture, woodland and channel banks
Owens and Walling, (2002)	River Tweed, UK	Geological sub-areas; topsoil and subsoil (channel bank) sources
Walling *et al*. (1999b)	River Ouse, UK	Geological sub-areas and tributary sub-basins; arable, pasture and channel banks
Walling and Woodward, (1995)	River Culm, UK	Geological sub-areas; arable, pasture and channel banks

1.5 Significance of Study Area

The River Lugg catchment has historically provided excellent salmonid spawning and juvenile habitats, which is important for salmonid health in the wider Wye catchment (Jarvie *et al.,* 2003). In the past, the Wye supported a world-famous salmon fishery (Thomas and Blakemore 2007), with both the Wye and Lugg possessing healthy populations of Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*). However, salmon stocks in the Wye catchment have shown a significant decline since 1985, with juvenile salmon numbers declining by 50% between 1985 and 2004 (Clew *et al.,* 2010). As a result, the status of Atlantic salmon in the River Lugg has been classified as being “suboptimal declining/unfavourable declining” (River Lugg Conservation Strategy, 1996), although recent analysis has shown a slight upward trend in juvenile salmon densities between 2002 and 2015 (Natural Resources Wales, 2015). Previous studies have highlighted the potential causes for this rapid decline, attributing diffuse pollution and increased fine sediment inputs as major contributing factors for the degradation of spawning and juvenile habitat, and the subsequent reduction in salmonid numbers (Soulsby *et al*., 2001; Naden *et al*., 2003; Suttle *et al*., 2004; Heywood and Walling 2007; Kemp *et al.,* 2011; Sear *et al.,* 2016). The River Lugg is therefore a priority catchment identified by the CSF scheme, where episodic high sediment loadings have contributed to the catchment failing to achieve WFD ‘good ecological status’.

The water quality of the River Lugg is important in order to maintain the good ecological status of the Special Areas of Conservation (SACs) in the Wye catchment (Whitehead *et al.,* 2010). However, the Lugg catchment provides a good example of the multiple pressures exerted on instream biota through several natural and human-induced factors, affecting its vulnerability to fine sediment inputs. For example, the catchment possesses easily erodible fine sandy soils overlaying Old Red Sandstone bedrock with high soil erosion risk (Jarvie *et al*., 2008), and there has been an increased coupling between farmed slopes, floodplain and the channel network, due to land drainage and channel modifications in the 1960s and 1970s. Reports suggest that this increasing siltation risk is due to changes in catchment land use and poor agricultural practice (Theurer *et al.,* 1998; Naden *et al*., 2003; 2016; Grabowski and Gurnell

2016; Schmidt *et al.,* 2018). Recent accelerated patterns of fine sediment transfer within the Lugg catchment have been linked to changing land use and land use practices towards an intensification in potato and strawberry farming. The former involves deep ploughing of field surfaces and the breakdown of soil structure, reducing the infiltration capacity, and creating pathways for enhanced sediment transport to the river network through rill and gully erosion (Theurer *et al.,* 1998). According to White (2003), 68% of potato fields within the Arrow catchment are located on a steep or moderate slope, where runoff might concentrate in compacted tramlines (Jarvie *et al*., 2008), which further exaggerates this problem. Strawberry growing can cause deep compaction, runoff and soil erosion, and involves the use of polytunnels, concentrating high runoff levels into small areas, owing to the large surface area of plastic. Both types of land use are high risk in terms of sediment loss, as they expose soils due to the lack of crop cover at times of the year when there is a higher tendency for extreme intensity rainfall.

The delivery of fine sediment from agricultural sources within the Lugg catchment is also associated with enhanced levels of sediment-bound nutrients, particularly Phosphorus (P) and Nitrate (NO_3), which bind to fine sediment particles (Haygarth *et al*., 2005; Edwards and Withers 2008). Studies have found the lower reaches of the Lugg catchment to exhibit high P and NO_3 levels due to the low dilution capacity and high agricultural inputs from the small agricultural tributaries, that confluence with the Lugg in the middle and lower reaches (Jarvie *et al.,* 2003). For example, Wade *et al.* (2007) attribute the high P levels to the recent expansion and intensification of livestock farming, with substantial rates also exported from arable crop cultivation, whereas Jarvie *et al.,* (2008) have found a 99% significant correlation between the percentage cover of arable land and subsequent NO_3 concentrations, related to the use of fertilisers in intensive arable cultivation. Diffuse loads of sediment and associated nutrients from agriculture are therefore of great concern within the catchment (Jarvie *et al.,* 2005).

1.6 Rationale

The development of an improved evidence base regarding the key sources of contemporary sediment fluxes is seen as a key requirement for informing the effective implementation of catchment management strategies to help reduce the sedimentation problem (Collins *et al.,* 2010c; 2017). Managing the issues of fine sediment input requires a catchment-scale approach (Sear *et al.,* 2009) underpinned by science that links land and water phases of fine sediment transfer and storage and integrates it with the policy and management communities. However, previous studies into fine sediment dynamics have either focused on identifying potential sediment contributions from individual source types or those that are spatially-constrained to sub-catchment scale or focused on sediment contributions from different geological zones at the catchment scale (Table 1.1). Only a limited number of studies have adopted a more holistic approach that traces the origins of catchment-scale sediment pollution based on individual sub-catchments and the identification of individual source types at the sub-catchment scale.

The Lugg catchment is a priority area under the CSF scheme, however, underpinning scientific evidence on catchment scale sources of fine sediment in the catchment is not available. Against the background of a clear need for improved sediment source information in the Lugg catchment and the success of the fingerprinting approach in providing such data in other environments, this research project will use a composite sediment fingerprinting procedure to establish the relative contribution of several potential sediment source types to the sediment yield of the River Lugg. Although this method has been successfully used in other CSF catchments (e.g. Dorset Frome, Exe and Axe) to help manage fine sediment, it has not been readily deployed in the Lugg catchment to address the problem of fine sediment delivery in a management context. However, a limited number of previous studies have investigated sources of sediment in small sub-catchments within the Lugg catchment. For example, a small headwater basin of the River Lugg, managed as an experimental unit, has been of particular interest for suspended sediment sources (Russell *et al*., 2001; Walling *et al*., 2002). Walling *et al*. (2008) traced sources of sediment in the Stretford Brook sub-catchment as part of the

PSYCHIC project. Burke (2011) also used the sediment fingerprinting approach to identify sources of sediment during two salmonid spawning seasons in the Lugg catchment. Nevertheless, none of these studies occurred over a large temporal timeframe or were applied at the catchment scale in a management context.

Despite the need for long term studies (ca. 3 years) to monitor fine sediment delivery and provenance at the catchment scale, such studies are limited. The majority of previous studies monitor over a 12-24-month period (e.g. Russell *et al*., 2001; Walling *et al.,* 2002). This could present problems with anomalies of patterns in particular years with particular seasonality of flood events, which could have implications for fine sediment yield. This research will therefore focus on a lengthier 42-month study of sediment provenance at the catchment scale to develop an enhanced assessment of spatial and temporal patterns in fine sediment pollution and provide a readily applicable method for catchment managers in the Lugg to identify catchment-wide sources of fine sediment input. This will allow the implementation of targeted mitigation measures in areas that are prone to sediment pollution in order to reduce the impact of excessive sediment pollution.

Furthermore, concern over sediment problems in the River Lugg, including accumulation of fine sediment on the channel bed and elevated turbidity levels during periods of stable flow, provided the stimulus for a detailed study of catchment sediment dynamics. The evidence base to investigate episodic high sediment loadings in the Lugg catchment is established on monthly ‘spot’ samples collected by the Environment Agency. These samples are unlikely to provide representative information on suspended sediment concentrations and sediment loads within the catchment as high flow events outside of the monthly sampling pattern will be ignored. Anthony and Collins (2006) reported that annual average suspended sediment concentrations calculated from monthly spot samples were significantly lower than actual suspended sediment concentrations during high flow events. Therefore, there is an important need for further empirical evidence regarding suspended sediment sources (Russell *et al.,* 2001). By developing a continuous record of flow and suspended sediment at key sites in the catchment, this research will address this ‘research gap’.

The implementation of this research programme in the Lugg catchment will therefore provide a case-study to assess the applicability of the approach to other catchments nationwide, where an integrated, transferable assessment at the catchment scale will aim to provide underpinning scientific evidence for effective sediment management. Such an integrated assessment and monitoring approach can be used by catchment managers and stakeholders for continued surveillance of the Lugg and exported to other UK catchments of where fine sediment pollution is a concern.

1.7 Aims and Objectives

Against the background context and rationale identified in the preceding sections, the aim of this research project is: *To investigate the sources and patterns of fine sediment movement in the Herefordshire Lugg catchment using an extensive spatial and temporal monitoring and modelling approach, in order to help target resources to reduce the impact of excessive siltation.*

In order to achieve this aim the following research objectives have been established:

1. To assess the spatio-temporal variations in suspended sediment delivered to key monitoring sites.

Given the concerns about fine sediment pollution in the catchment and the failure of the River Lugg to achieve WFD ‘good ecological status’, this objective focuses on exploring the relationship between high suspended solids and siltation through the provision of a long-term monitoring record at key sites.

2. To identify catchment scale sources of fine sediment and evaluate the spatio-temporal variations in fine sediment contributions delivered to key monitoring sites.

This objective aims to determine the spatial provenance of fine sediment by identifying particular tributary sub-catchments that persistently deliver sediment to key sites over different flow events. By utilising a recognised sediment fingerprinting and mixture modelling approach, this objective will establish any spatial and temporal variations in the main contributors of siltation in the River Lugg catchment.

3. To identify and evaluate sub-catchment sources of fine sediment based on differing land use types.

Given the findings of Theurer *et al.,* (1998), where significant connections between increasing siltation risk, catchment land use and poor agricultural practice were recognised, this objective concentrates on developing an enhanced assessment of fine sediment sources in key sub-catchments. By refining the sediment fingerprinting and mixture modelling approach to improve the ability of the composite fingerprint to discriminate between source types, this objective will establish any relationships between specific land uses and the contributions of fine sediment.

4. To develop a monitoring strategy for fine sediment provenance at a catchment scale that will provide underpinning scientific evidence for effective sediment management.

Sustainable catchment sediment management requires an appropriate scientific underpinning that has established the temporal character of fine in-channel sediment and its sources within the wider catchment. By utilising a coupled field monitoring and mixture modelling approach that identifies catchment wide sources of fine sediment input, this objective will distinguish priority areas, that pose the greatest risk of being fine sediment pollution sources, for practical sediment management.

1.8 Thesis Structure

The research aim and objectives of this study are addressed through the following structure:

Chapter 1: Introduction
The background to the sediment problem and the rationale of the

⇓

Chapter 2: Study Catchment
The environmental settings of the Herefordshire Lugg catchment

⇓

Chapter 3: Methodology
The research approach and field and laboratory methods adopted within the research project

⇓

Chapter 4: Spatio-Temporal Variations in Suspended Sediment
The field monitoring results and interpretation from the key monitoring sites

⇓

Chapter 5: Statistical Procedures and Fingerprinting Technique
The statistical methods and refinements of the sediment source fingerprinting technique

⇓

Chapter 6: Fine Sediment Sources at the Catchment Scale
The catchment scale sediment fingerprinting results, analysis and interpretation

⇓

Chapter 7: Sub-Catchment Scale Sediment Fingerprinting Statistical Results
The statistical results from the sediment fingerprinting technique

⇓

Chapter 8: Fine Sediment Sources at the Sub-Catchment Scale
The sub-catchment scale sediment fingerprinting results, analysis and interpretation

⇓

Chapter 9: Conclusions
Main conclusions, limitations and recommendations for future

CHAPTER 2
STUDY CATCHMENT

2.1 Introduction

In this chapter, the environmental background of the Lugg catchment is described, summarising the catchment settings and current hydrological regime. Information on the underlying geology and soil type, along with the existing land use is also presented.

2.2 Catchment Setting

The River Lugg has a catchment area of 1077 km^2. It is a significant tributary of the River Wye, which has been designated a site of Special Scientific Interest (SSSI) under the EU Habitats Directive (92/43/EEC). The lower reach of the Wye catchment is an Area of Outstanding Natural Beauty (AONB) and is considered to be of high ecological value (Wade *et al.,* 2007). Both the Rivers Lugg and Wye have been nominated as European Special Areas of Conservation (SAC) on account of their rich wildlife and habitat, including the nationally recognised Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*) fishery (Whitehead *et al.,* 2010).

The River Lugg flows in a south-easterly direction from its source near Llangunllo in Powys, Wales, across the Welsh-English border beyond the town of Presteigne and into Herefordshire. It is joined by the River Arrow (catchment area of 290 km^2) in its middle reaches immediately downstream from the town of Leominster and the River Frome (catchment area of 172 km^2), before reaching its confluence with the River Wye, downstream of the city of Hereford (Figure 2.1). It is characterised by both upland and lowland areas, where the typical catchment elevation varies from 293 m in the upper parts to 158 m in the lower reaches (Marsh and Hannaford, 2008).

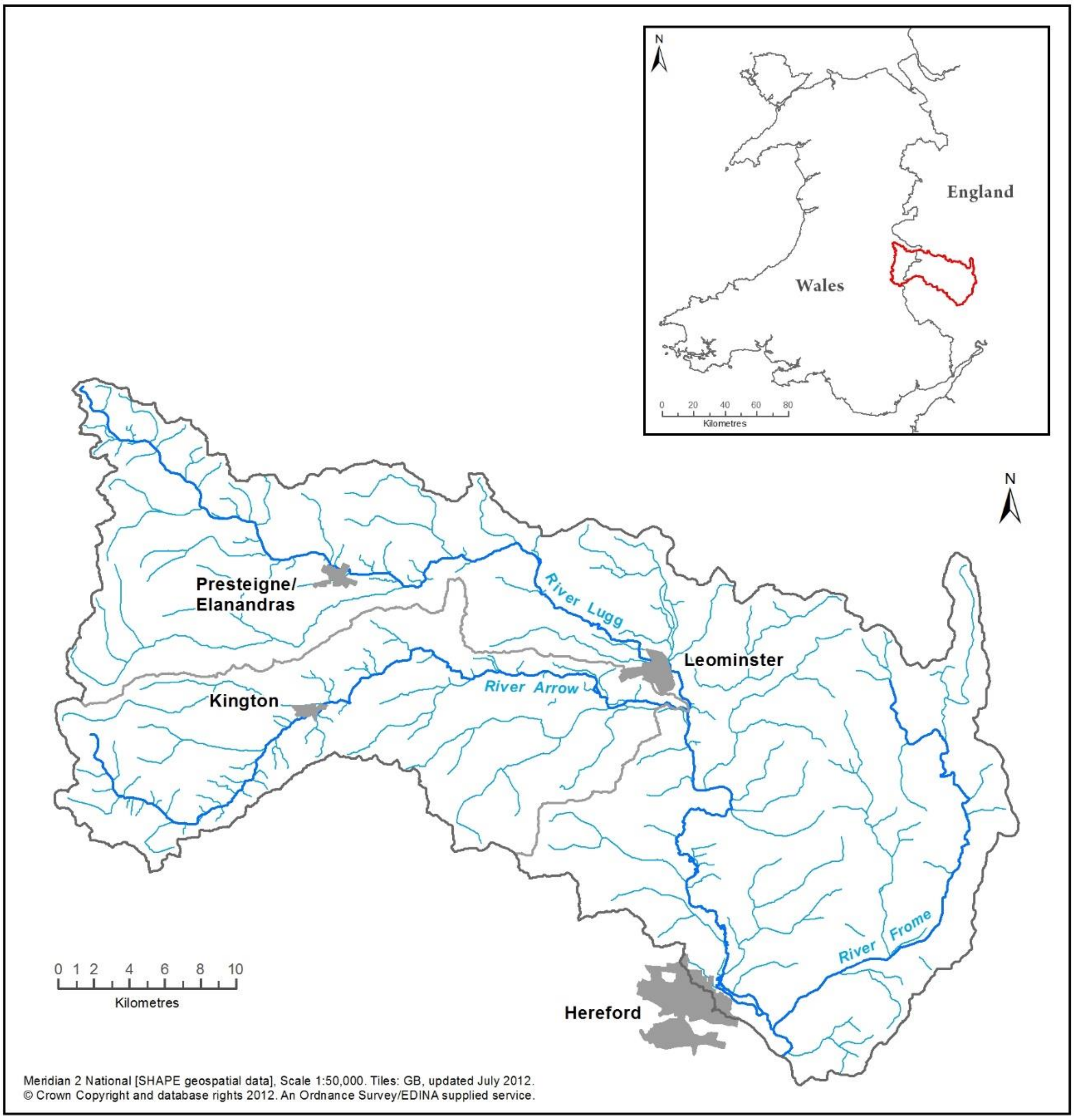

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Figure 2.1 The location of the River Lugg catchment within the UK.

2.3 Geology

The geology of the Lugg catchment can be described as essentially homogeneous in nature, predominantly underlain by Old Red Sandstone (Russell *et al*., 2001; Jarvie *et al.,* 2008). The Rivers Arrow and Lugg rise on the Silurian Ludlow beds, flow over the mud, silt and sandstones of the Silurian Llandovery rocks, then Wenlock limestones and shales as it crosses the English border, before encountering the Lower Devonian and Pridoli rocks, dominated by Old Red Sandstone just upstream from Leominster (Figure 2.2).

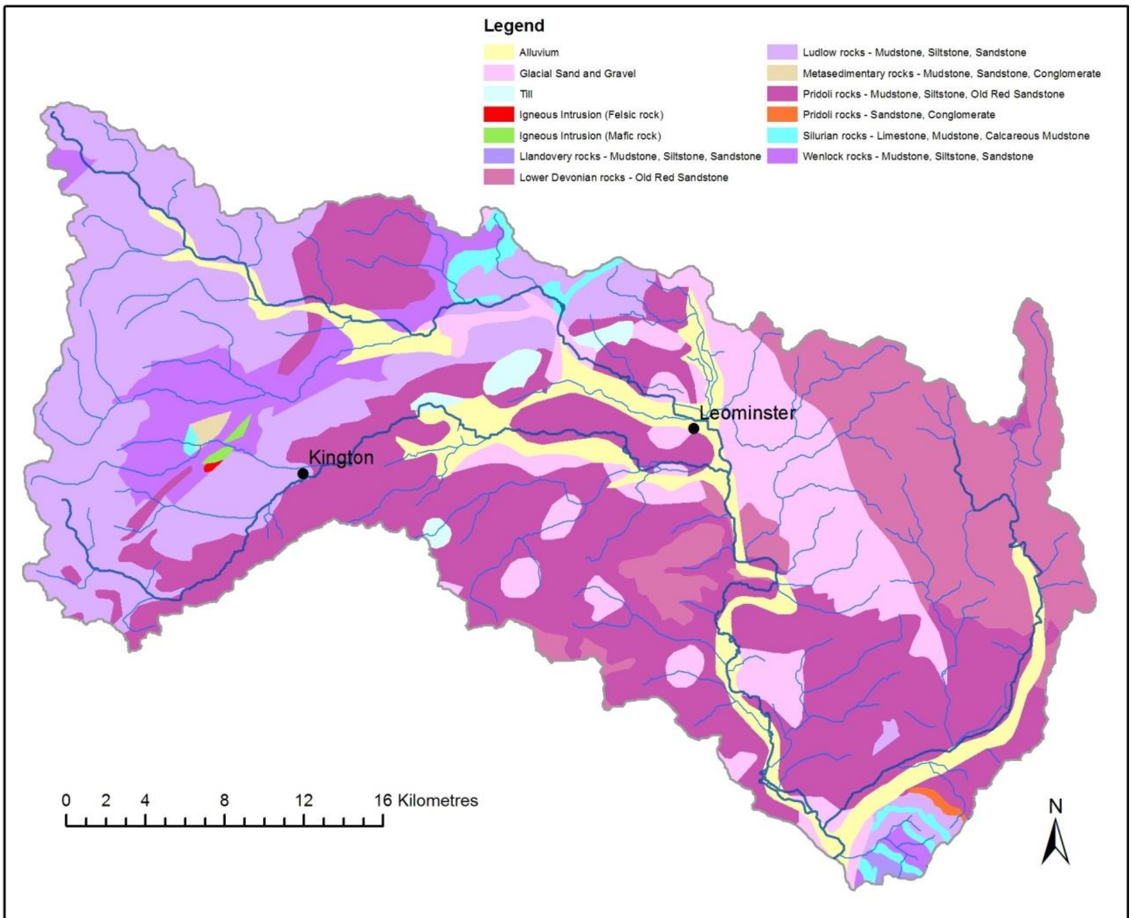

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Figure 2.2 Geology of the Lugg catchment (bedrock and superficial).

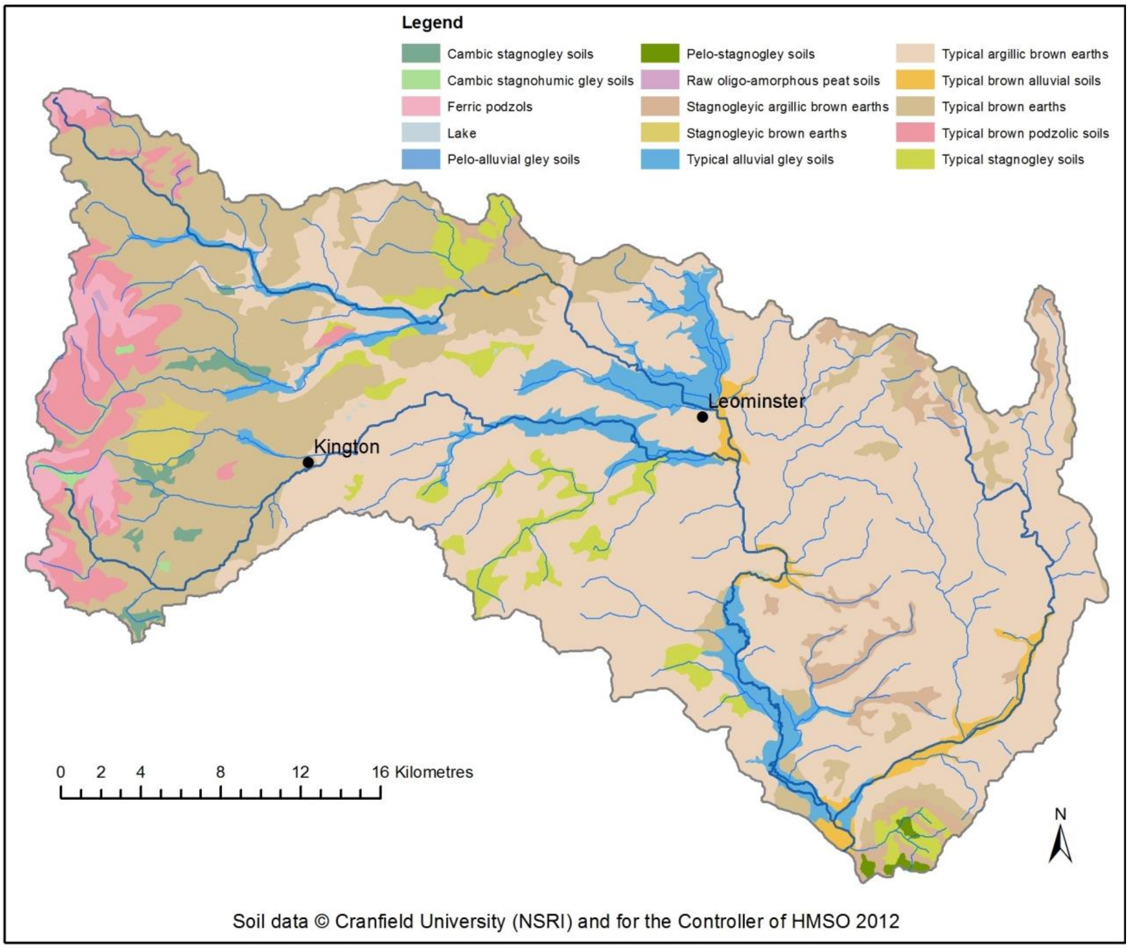
The headwaters drain an upland area, including Radnor Forest, which is underlain by impermeable Silurian Ludlow rocks, comprised of mudstones and siltstones, with outcrops of Silurian limestone, shales, grits and sandstones (Jarvie *et al.,* 2003). The bedrock geology here is the principal influence on channel form, and typically has a high-energy erosive nature (Burke 2011). These impermeable formations are covered by extensive alluvial gravel and sand deposits in the valleys, which provide high base-flow conditions and moderate flood peaks (Marsh and Hannaford 2008).

The lowland catchment is underlain by Lower Devonian and Pridoli rocks, dominated by Old Red Sandstone, comprising readily-weathered marls of the Herefordshire lowlands (Jarvie *et al.,* 2003). It comprises beds of easily eroded red and greenish-grey silts and locally calcareous mudstone, producing subdued relief and a meandering channel form. This bedrock geology moderates the high flow peaks during heavy rainfall events considerably, giving a base flow index (BFI) of 0.66, indicating the dominance of groundwater in the lower parts of the catchment (Wade *et al.,* 2007; Whitehead *et al.,* 2010). The mixture of the impervious Silurian headwater geology and the more permeable sandstone with extensive deposits of drift geology in the lower reaches of the Lugg catchment provides a significantly higher base flow than would be observed in an entirely impermeable catchment. For instance, groundwater dominated rivers typically have a mean BFI of 0.68-0.83, with the more impermeable lithologies exhibiting a BFI of 0.38-0.49 (Sear *et al.,* 1999).

Drift deposits overlaying the bedrock are evident across the catchment, with extensive alluvial deposits located along the riparian zone, deposited as a result of flooding for several millennia (Ragg *et al.,* 1984). Glacial sands and gravels can be found around Leominster, with further small outcroppings of till located in the middle reaches. These deep fluvioglacial deposits are worked for sand and gravel production (Marsh and Mordiford, 2008), notably around the area north of Hereford.

2.4 Soils

The underlying geology has a significant influence on soil type within the Lugg catchment. Soils in the catchment are typically silty-clay loam in texture and, historically, field drains have been installed across large areas (Jarvie *et al.,* 2008). The extreme upper parts of the catchment, covering upland areas, including Radnor Forest, exhibit well drained fine loamy or fine silty soils which overlie bedrock and loamy permeable soils with a wet peaty surface. Before the Rivers Arrow and Lugg reach the English border, they intersect a unit of well-drained silty soils before reaching an extensive area of reddish sandy loam soils, associated with the underlying Old Red Sandstone (Figure 2.3).



Soil data © Cranfield University (NSRI) and for the Controller of HMSO 2012

Figure 2.3 Soils map of the Lugg catchment.

The soil established in the Lugg catchment can be classified into three main types. The Barton series (typical brown earths) are mainly located in the upper regions and are composed of well-drained silty soils overlaying siltstone. This series can be shallow in some places with soils at a slight risk of water erosion. The Escrick series (typical argillic brown earths) dominate the middle and lower reaches of the Lugg and consist of deep, well-drained reddish coarse loamy soils. Their pedogenic characteristics are strongly influenced by the underlying Old Red Sandstone bedrock and are particularly erodible during heavy rainfall events, particularly when the soil surface is unvegetated. Storm runoff from fields and farm tracks are exceptionally turbid (Jarvie *et al.,* 2008) as the fine material is easily suspended. This soil type is also subject to desiccation during the low rainfall interval of the summer, which can also accentuate the erodibility of the soil (Walling *et al.,* 2002). The Conway (typical alluvial gley soils) and Teme series (typical brown alluvial soils) are located principally along the riparian zones throughout the catchment and consist of deep fine silty and clayey river alluvium. These soils carry a risk of flooding, effected variably by groundwater that can be located less than 2 m from the surface.

Some small areas of Middleton (stagnogleyic argillic brown earths) and Compton series (pelo-alluvial gley soils) can be found at the base of the slopes, in hollows and along the riparian zone throughout the middle and lower reaches (Russell *et al.,* 2001). The former consists of reddish silty shale and siltstone with subsoils of low permeability, whilst the latter consists of reddish clayey soil which is affected by groundwater.

2.5 Land Use

Table 2.1 presents land cover information for the Lugg catchment. The catchment can be described as rural in nature, with land use dominated by pasture and arable production. The upper reaches of the catchment drain low-intensity grazing land and are dominated by grassland and woodland (Lord and Anthony, 2000), with small areas of bog and heathland confined to the extreme upper parts. There is a notable change in prevailing land use in the Arrow and Lugg as they flow into the county of Herefordshire and through the town of Leominster, where both encounter numerous small agricultural tributaries (Jarvie *et al.,* 2003). Intensive arable cultivation becomes the dominant land use throughout the middle and lower parts of the catchment (Wade *et al*., 2007), with several fields occupied by longer-term pasture and woodland scattered along the riparian zone of the main channel (Figure 2.4).

Table 2.1 Land cover data for the Lugg catchment (based on the Land Cover Map 2007 data).

Land cover category	**Area (%)**
Grassland	45.7
Arable	40.5
Woodland	9.9
Urban	1.5
Heath	2.1
Bog	0.1
Freshwater	0.2

The land use within the Lugg catchment is mainly dominated by agriculture, which is of a great economic importance. The type of agriculture varies considerably, owed largely to the topography (Jarvie *et al*., 2003). For example, livestock production, particularly sheep farming, is the main agricultural activity in the harsh and marginal upland areas, with areas of natural woodland, whereas arable cultivation dominates the lowland areas. In the upper and middle parts of the catchment there are areas of hopyards, fruit orchards, predominantly apples for cider production, and woodland (Walling *et al.,* 2002). Intensive arable and dairy farming dominate the lower reaches of the catchment (Whitehead *et al.,* 2010), with some pig and poultry production located around the River Arrow sub-catchment and to the south of Leominster (Wade *et al.,* 2007). Winter cereal is the primary arable crop, including maize, peas, turnips, field beans and oil seed rape; however, potato and strawberry farming have become increasingly important throughout the middle and lower parts of the catchment (Jarvie *et al*., 2008).

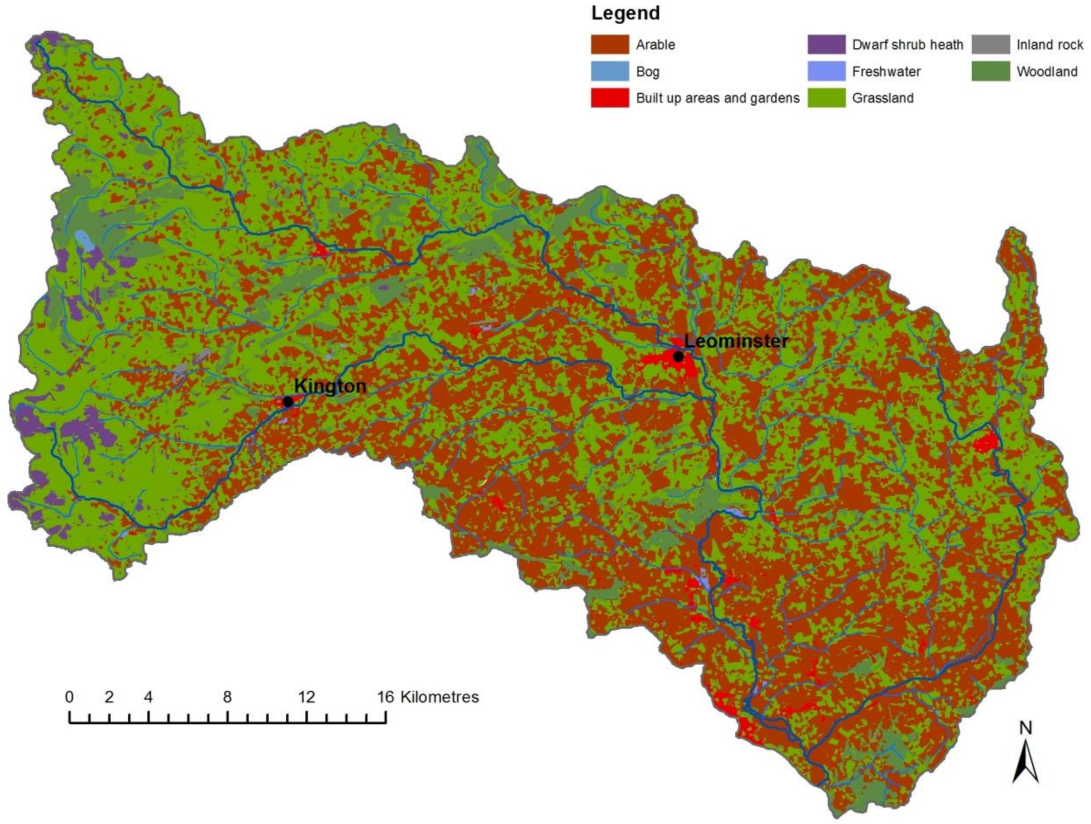


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Figure 2.4 Land cover map of the Lugg catchment.

Industry and urbanisation is limited within the catchment and confined to the lower parts of the catchment. Heavy industry (non-ferrous metal processing and natural gas fired power production) is restricted to Hereford, with other low-level industrial activities, including quarrying and timber production and food processing, existing in and around Hereford and Leominster (Jarvie *et al.,* 2003).

2.6 Hydrological Regime

Throughout the Lugg catchment, six gauging stations and eight rain-gauges assist to provide valuable flow, rainfall information, and catchment summary statistics (Figure 2.5). The natural discharge variability of the River Lugg is fundamental to maintaining river and stream ecosystem integrity (Tetzlaff *et al.,* 2008). The hydrological regime alters owing to differences in the underlying geology and spatially-variable precipitation. For example, high precipitation and the impermeable Silurian headwater geology in the upper parts of the catchment tend to create a flashy flow river regime (Jarvie *et al*., 2003). Infiltration rates are consequently low, with elevated overland rates promoting soil erosion during heavy rainfall events. Elevated runoff is supported through the relatively high mean runoff rate of 613 mm observed in the upper parts of the catchment (Marsh and Hannaford 2008). In the lower reaches where the underlying geology is more permeable, the river network exhibits a less variable flow regime (Jarvie *et al.,* 2003). During flood events, groundwater-fed sources contribute to the increased flow established in the lower parts of the catchment. As a consequence, mean runoff rates are relatively low in comparison to the upper parts of the catchment.

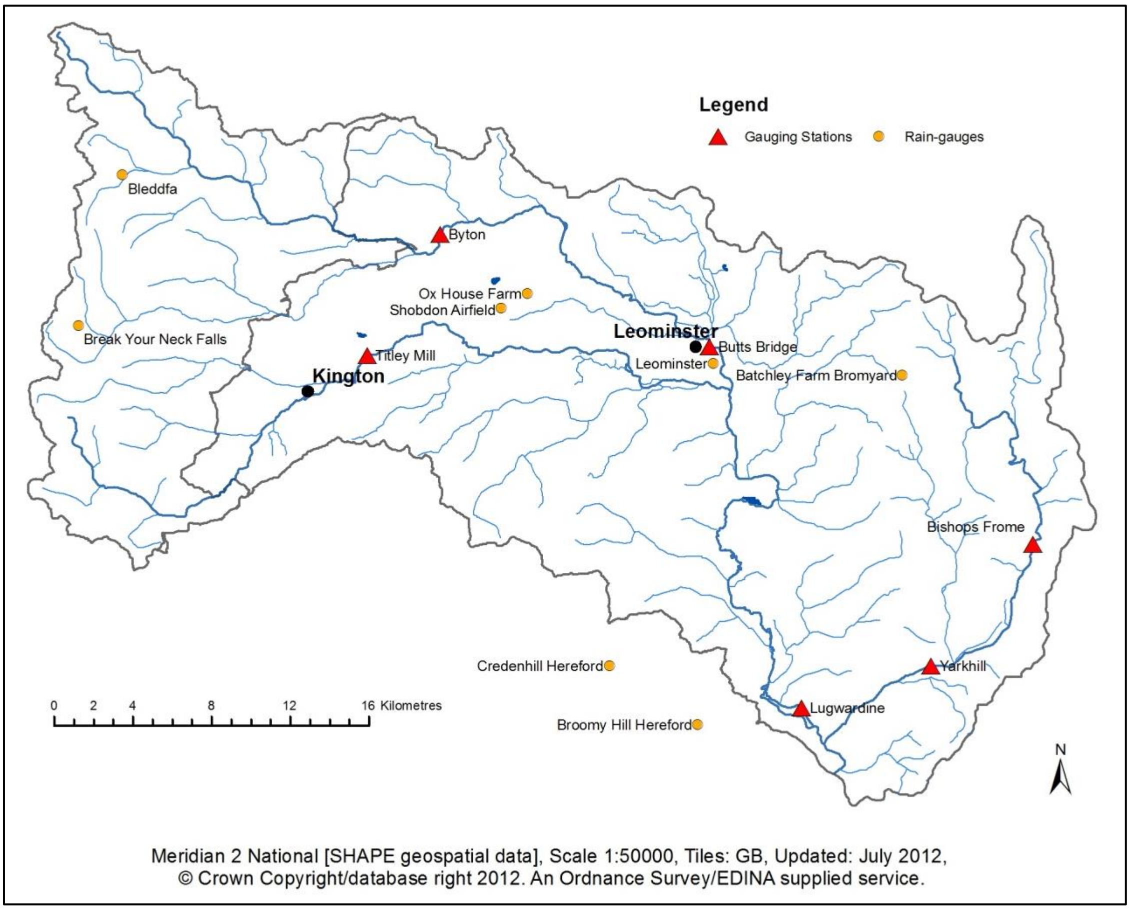

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Figure 2.5 Location of gauging stations and rain gauges within the Lugg catchment.

The region exhibits a temperate maritime climate, with an average temperature of 10.2 °C and monthly rainfall spread relatively consistent throughout the year. This leads to winter flows that are generally quite high, with elevated flood risk and summer flows that are much lower, with episodic storm events creating occasional high-flows. However, climate change scenarios indicate that high intensity rainfall events are likely to become more frequent, increasing flood frequency (Hulme *et al.,* 2002). The 90 percentile flow (Q_{10}) ranges between 8.78 $m^3\ s^{-1}$ in the upper parts of the catchment, and 26 $m^3\ s^{-1}$ in the lower reaches. The River Lugg therefore has the capacity to transport large quantities of sediment during high rainfall events (Wade *et al*., 2007).

Mean discharge on the Lugg varies from 3.94 $m^3\ s^{-1}$ on the upper Lugg (Byton), 5.95 $m^3\ s^{-1}$ (Butts Bridge), through to 10.75 $m^3\ s^{-1}$ on the lower Lugg (Lugwardine). Its main tributary, the River Arrow, exhibits a mean discharge of 2.38 $m^3\ s^{-1}$ (Titley Mill) and the mean discharge in the River Frome, a smaller tributary that joins close to the Lugg's confluence with the Wye, varies from 0.74 $m^3 s^{-1}$ in the upper reaches (Bishops Frome) to 1.18 $m^3 s^{-1}$ in the lower reaches (Yarkhill). Precipitation within the catchment is spatially-variable, with average annual rainfall totals (2005-2012) in the upper parts of the catchment almost double that found in the lower reaches. The average number of 'wet' days where over 10 mm of rainfall accumulates range from 36 days in the upper parts of the catchment to 16 days in the lower catchment. The long-term (1961-2006) annual mean rainfall statistics also show a spatially-variable pattern across the catchment, with totals averaging around 1041 mm and 731 mm in the upper and lower reaches respectively. Approximately 613 mm of runoff is generated in the former and 256 mm in the latter (Wade *et al*., 2007). Summary flow and catchment statistics for the Lugg catchment can be found in Tables 2.2 and 2.3.

Table 2.2 Summary flow and catchment statistics at gauging stations for the Lugg catchment (adapted from the National River Flow Archive, 2016).

Parameter	**Lugg at Byton**	**Lugg at Butts Bridge**	**Lugg at Lugwardine**	**Arrow at Titley Mill**	**Frome at Bishops Frome**	**Frome at Yarkhill**
Grid Reference	SO 364647	SO 502589	SO 548405	SO 328585	SO 667489	SO 615427
Catchment Area (km^2)	203.3	371.0	885.8	126.4	77.7	144.0
Altitude (min-max) (mAOD)	124.3 – 659.7	68.9 – 659.7	46.7 – 659.7	129.8 – 540.2	76.9 – 252.4	57.2 – 252.4
Base Flow Index	0.65	0.65	0.64	0.56	0.47	0.52
Mean Flow (m^3 s^{-1})	3.94	5.95	10.75	2.38	0.74	1.18
95% Exceedance (Q_{95}) (m^3 s^{-1})	0.64	0.95	1.53	0.28	0.07	0.16
70% Exceedance (Q_{70}) (m^3 s^{-1})	1.44	2.09	3.90	0.77	0.19	0.34
50% Exceedance (Q_{50}) (m^3 s^{-1})	2.61	3.73	6.67	1.46	0.33	0.62
10% Exceedance (Q_{10}) (m^3 s^{-1})	8.78	13.00	26.00	5.52	1.53	2.51
Peaks Over Threshold (POT) (m^3 s^{-1})	15.73	23.36	31.19	16.39	N/A	12.65
1961-2006 Average Annual Rainfall (mm)	1041	926	847	1018	743	731
Runoff (mm)	613	473	392	590	287	256

Table 2.3 Summary precipitation statistics at rain-gauges in and around the Lugg catchment (adapted from the Met Office and Environment Agency data sets).

Precipitation Parameter	**Break Your Neck Falls**	**Bleddfa**	**Shobdon Airfield**	**Ox House Farm**	**Leominster**	**Batchley Farm Bromyard**	**Credenhill Hereford**	**Broomy Hill Hereford**
Grid reference	SO 181600	SO 203676	SO 396609	SO 409616	SO 503580	SO 600574	SO 451427	SO 496397
Average annual rainfall (2005-2012) (mm)	1128.4	1137.6	745.6	725.3	636	764	679.7	673.7
Mean number of days > / = 0.2 mm (‘rain’ days) rainfall	237	244.1	206.4	150.6	173	170.4	190.9	169.9
Mean number of days > / = 1 mm (‘rain’ days) rainfall	158	159.5	124	115.4	111.9	118.6	113.5	115
Mean number of days > / = 10 mm (‘wet’ days) rainfall	36	35.3	19.8	19.8	15.8	21.1	17.4	17.8

2.7 Summary

This chapter has detailed the background environmental characteristics of the Lugg catchment, encompassing information on the underlying geology, soil type, existing land use, and hydrological regime. It is apparent that the environmental setting gives rise to spatially-variable precipitation that impacts considerably on the hydrologic regime of the River Lugg. The underlying geology and soil type and associated existing land use differs spatially within the catchment, with a distinctive upper-lower divide. The elevated rainfall amounts, impermeable Silurian geology and well-drained silty soils located in the upper parts of the catchment create a flashy flow river regime. As a consequence, the typical land use in these areas is confined to rough grazing land dominated by grassland and woodland. However, in the lower parts of the catchment the permeable sandstone and drift deposits overlain by fine sandy soils, give rise to intensive arable cultivation. Although precipitation amounts are much lower than that of the upper catchment, creating a more gradual and less variable flow regime, the soils are easily eroded during heavy rainfall events, generating turbid runoff from fields and farm tracks. The River Lugg is therefore capable of transporting high amounts of fine sediment during these events.

CHAPTER 3
METHODOLOGY

3.1 Introduction

This chapter details the field and laboratory methods adopted within the research, and the role of the Stakeholder Advisory Group that was established as part of the research process. The approach used for selecting suitable monitoring sites within the Lugg catchment is outlined along with the monitoring strategy implemented. The techniques used for collecting potential source material within the catchment and the collection of suspended sediment samples over specific flood events, and the laboratory procedures applied during sample preparation and analysis are also detailed.

A Stakeholder Advisory Group was formed to enable comprehensive consultation and provision of information throughout the entire research process (*cf*. Lane *et al.,* 2011). The group consisted of representatives from key stakeholders in the Lugg catchment. Table 3.1 details the members of the Stakeholder Advisory Group and their involvement. All members either had an invested interest in the project (i.e. funders) or had an interest in water quality and diffuse pollution in the Lugg catchment, and were therefore chosen as being suitable stakeholders to provide guidance and influence research outcomes. Their involvement included advising on the project formulation, feeding back on the proposed research design, providing iterative feedback on the results, and contributing local knowledge that helped in ground truthing. They also assisted in project dissemination through publishing articles and organising community engagement events. Throughout the project 6-monthly meetings with the Advisory Group were organised to review progress and provide continuing guidance on the research. A wider group of members from other interested stakeholders were invited to attend these meetings and provide catchment knowledge to help ground truth results (Table 3.2). This iterative engagement with the group ensured that mutual knowledge concerning the Lugg catchment was frequently exchanged.

Table 3.1 The members of the Stakeholder Advisory Group and their involvement in the project.

Organisation	Member	Role
Environment Agency	Peter Gough (Senior Technical Specialist – Fisheries)	Provided problem context and background environmental quality and fish health data
Environment Agency	Jeremy Churchill (Environment Officer, Lower Wye and Herefordshire)	Provided problem context and advice of WFD objectives for the catchment
Natural England	Sarah Olney (Catchment Sensitive Farming Officer for the Lugg catchment)	Provided local knowledge of the catchment, assisted with land access and worked to implement practical measures
ARUP	David Hetherington (Principal Water Scientist)	Provided feedback on the research design and advice on water quality science
Herefordshire Nature Trust	Colin Cheeseman (Chief Executive)	Provided local knowledge and project dissemination

Table 3.2 The members of other interested stakeholders providing knowledge of the Lugg catchment throughout the project.

Organisation	Member
Lugg and Arrow Fisheries Association	Tony Norman (Farmer)
Lugg and Arrow Fisheries Association	David Forbes (Farmer)
Wye and Usk Foundation	Simon Evans (Chief Executive Officer)
Environment Agency	Jason Jones (Fisheries Technical Officer)
Natural England	Steven Bailey (Catchment Sensitive Farming Co-ordinator Severn Basin)
Natural England	Helen Wake (Senior Advisor, Diffuse Water Pollution)

Figure 3.1 outlines the conceptual model of sediment source fingerprinting for establishing suspended sediment sources within a catchment (Collins and Walling, 2002). High magnitude storm events can lead to the erosion and subsequent mobilisation of sediment from various catchment sources. These sources could vary spatially from different geological sub-areas or different tributary sub-basins. Sources could also vary by ‘type’, including surface sources generated from differing land use practices, and sub-surface sources such as material from eroding channel banks. The sediment mobilised from the potential sources within a catchment is mixed during transport processes. Individual source types can be discriminated by a comparison of the source material and the suspended sediment delivered to the ‘sink’ sites, using a statistically-verified combination of properties that form a composite fingerprint (Collins *et al*., 1998; 2010b). The integration of the concentration of the fingerprint properties into a multivariate numerical mixing model (Owens *et al.,* 1999; Walling *et al*., 1999b) enables the apportionment of the relative contributions of sediment from the potential sources.

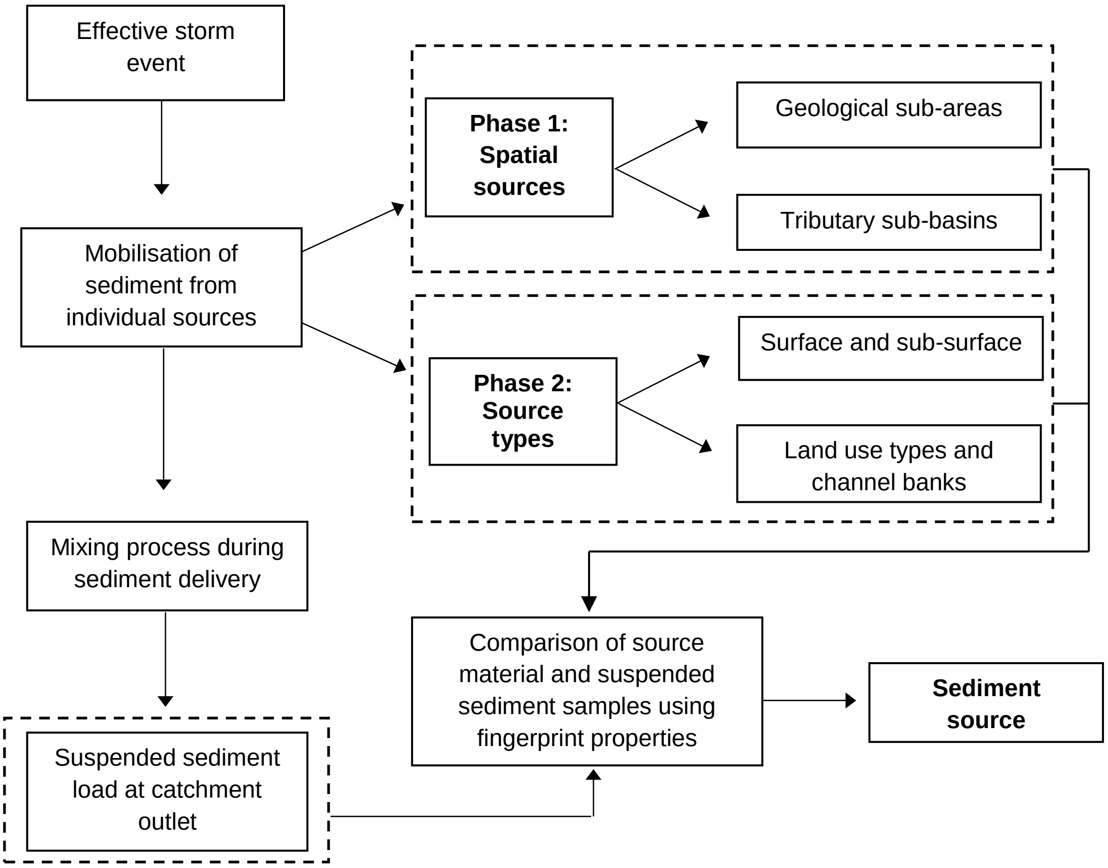

Figure 3.1 Conceptual model of sediment source fingerprinting adapted from Collins and Walling 2002; Walling *et al*., 2008).

The research design was divided into two phases, utilising this sediment fingerprinting technique to identify the sources of fine sediment being delivered to key sites in the Lugg catchment. The first phase was concerned with assessing the spatial and temporal variations in suspended sediments and identifying fine sediment sources at the catchment scale. The fingerprinting technique developed during this phase was therefore based on spatial sources of fine sediment. The second phase focused upon identifying fine sediment sources in significant sub-catchments distinguished through the sediment source ascription of the first phase. The fingerprinting procedure employed during this phase was established on individual source types. The following sub-chapters detail the field sampling approach developed in each phase, and the rationale adopted for selecting key sites.

3.2 Catchment Scale Analysis

3.2.1 Study Sites Selection

In order to assess the spatial and temporal variations in the character of fine sediments and their sources within the Lugg catchment, five monitoring ('sink') sites were set up at key locations (Figure 3.2). It was important to select the monitoring sites representative of the nature of fine sediment transfer within the entire catchment. Two monitoring sites were therefore located in the Arrow catchment, with one in the upper reaches (Site 1 - located at Hunton Bridge; site of an earlier monitoring station) and one in the lower reaches (Site 2 - located at Broadward Farm). The persistence and potential dilution effects of the enhanced sediment loadings in the River Arrow are relatively unknown at the catchment scale, so a monitoring station was installed just above the Arrow confluence on the River Lugg (Site 3 - located at Eaton Hall Farm) and just below the confluence (Site 4 - located at Marlbrook Farm). This monitoring strategy would enable any effects of high sediment loadings in the Arrow catchment on the Lugg to be identified. The final monitoring station was installed in the lower reaches on the Lugg (Site 5 - located at Lugwardine) to capture sediment information for the whole Lugg catchment. However, the more incised nature of the River Lugg towards its confluence with the Wye presented accessibility issues; this monitoring station was therefore located just before the convergence of the River Frome. The River Frome is a point-source dominated sub-catchment and is recognised as a siltation risk, with enhanced levels of phosphorous (Jarvie *et al.,* 2008). The siltation effects in the Lugg could therefore become diluted if a monitoring site was located downstream of the Frome confluence. Given this, and that the Advisory Group was predominantly interested in the issues of fine sediment in the River Lugg and Arrow, the Frome catchment was excluded from this study.

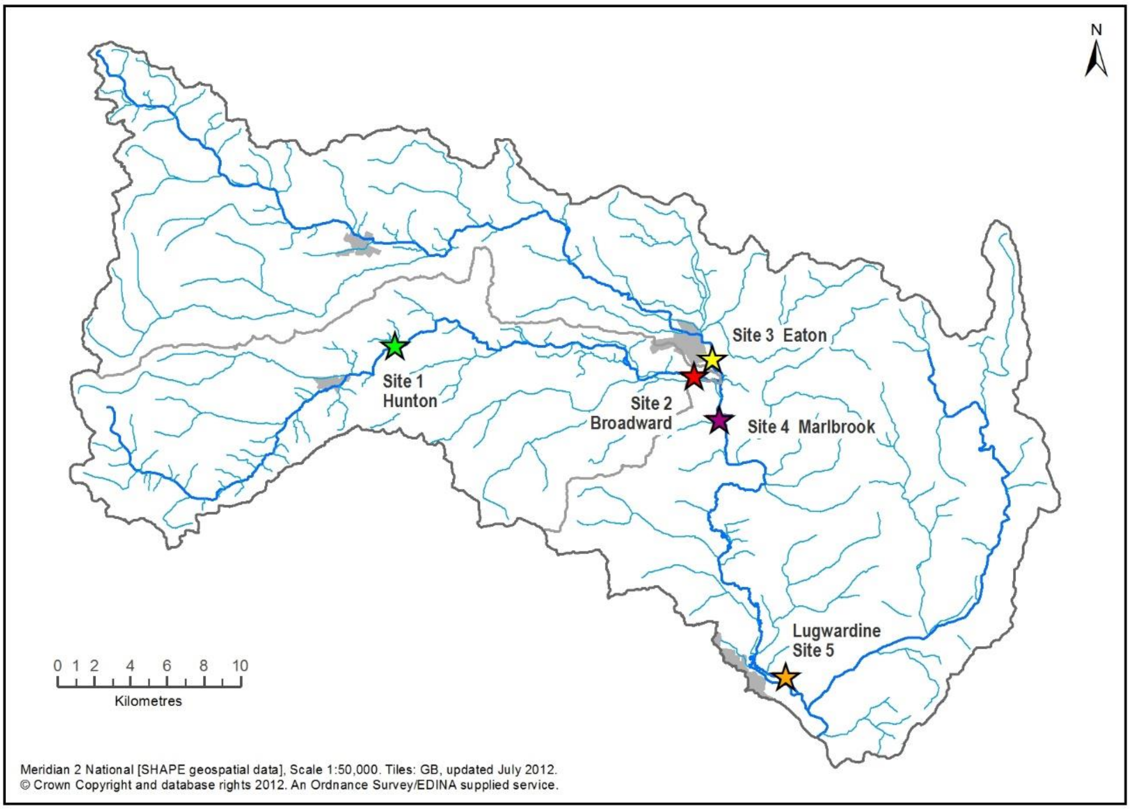

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Figure 3.2 The location of the monitoring sites within the Lugg catchment.

Analysis of sediment is often used as an indicator of spawning conditions and therefore these monitoring sites were located in areas with high quality salmonid spawning habitats. The locations of these monitoring sites were identified through large-scale field reconnaissance of potential sites, drawing on local knowledge from the Project Advisory Group. For example, the River Arrow, which is a main tributary catchment of the Lugg, has previously been identified by the Advisory Group as being particularly problematic in terms of high suspended sediment loads. This has subsequently been supported by a fine sediment study conducted between 2004 and 2008 (McEwen *et al.,* 2012).

Another important consideration when selecting suitable sites was access over the entire period of study. Therefore, it was essential to ensure that landowners were supportive of frequent site visits and monitoring equipment being installed on their land.

The criteria for selecting monitoring sites were four-fold. The first requirement was that monitoring stations should be located on channel reaches with pool-riffle morphology: environments that are likely to provide ideal salmonid spawning habitats (Armstrong *et al.,* 2003; Louhi *et al*., 2008). Secondly, monitoring stations should be in areas where spawning had been historically observed. This was identified through discussions with the Environment Agency, the Catchment Sensitive Farming Officer (CFSO) for the Lugg catchment, fisheries associations, and other stakeholders that have an interest in river habitat improvement in the area. Thirdly, sites needed to be accessible year-round to maximise temporal sampling resolution over the period of study. Lastly, the monitoring sites should be in areas where there is a sediment, or water quality-related problem. Secondary water quality (spot sampled suspended sediment concentrations and phosphate levels) and habitat data (invertebrate patterns and fish health), supplied by the Environment Agency, were therefore utilised to establish spatial variations and trends in habitat quality. Areas within the catchment that are particularly challenging and failing to achieve environmental targets set out in the EU WFD were consequently identified through this data analysis. Figure 3.3 shows the characteristics of each monitoring site in the Lugg catchment.

Each monitoring site was treated as a sediment sink site, receiving sediment from many different sub-catchments. This enabled the comparison of fine sediment inputs from the upper Lugg and the Arrow, and an understanding of their impact on fine sediment supply to the middle to lower Lugg. Summary characteristics of each monitoring site are shown in Table 3.3.

Upstream ***Downstream***

Site 1:
Hunton Bridge
(River Arrow)

Location:
SO 334587

Site 2:
Broadward Farm
(River Arrow)

Location:
SO 498570

Site 3:
Eaton Hall Farm
(River Lugg)

Location:
SO 508579

Site 4:
Marlbrook Farm
(River Lugg)

Location:
SO 512546

Site 5:
Lugwardine
(River Lugg)

Location:
SO 548405

Figure 3.3 Photos of upstream and downstream views at the five monitoring sites in the Lugg catchment.

Table 3.3 Summary characteristics of the monitoring sites.

Site	**Site 1 - Hunton Bridge**	**Site 2 - Broadward Farm**	**Site 3 - Eaton Hall Farm**	**Site 4 - Marlbrook Farm**	**Site 5 - Lugwardine**
Grid reference	SO 334587	SO 498570	SO 508579	SO 512546	SO 548405
Sink-catchment area (km^2)	129.22	288.42	367.35	672.34	885.45
Channel width (m)	10.3	12.2	13.2	17.5	12.5
Bankfull depth (m)	1.81	2.8	1.92	2.1	2.75
Armour layer D_{50} (mm)	47	47	30	61	42
Substrate matrix % <2 mm	15.8	38.7	33.7	26.3	70.5
Substrate matrix % <1 mm	10.9	32.3	27.1	21.5	63.3
Main land use	Pasture / Woodland	Pasture / Arable	Pasture / Arable	Arable / Pasture	Arable / Pasture
Dominant geology	Ludlow (Mudstone / Siltstone)	Pridoli (Siltstone / Sandstone)	Pridoli (Old Red Sandstone)	Lower Devonian (Old Red Sandstone)	Pridoli (Old red Sandstone)
Soil type	Well-drained silty soils	Well-drained reddish coarse loamy soils	Well-drained reddish coarse loamy soils	Well-drained reddish coarse loamy soils	Well-drained reddish coarse loamy soils / fine silty and clayey alluvium

3.2.2 Field Monitoring Strategy

A detailed and extensive monitoring strategy was developed in the Lugg catchment to complement the sediment source fingerprinting approach used to identify the sources of fine sediment. The monitoring strategy was implemented to establish the spatial and temporal patterns of suspended sediments delivered to the five monitoring sites between April 2009 and October 2012 (Table 3.4).

Table 3.4 Detailed monitoring periods adopted at each site.

Monitoring site	**Monitoring period**	
	Start	**Finish**
River Arrow		
Site 1 - Hunton Bridge	29 April 2009	26 October 2012
Site 2 - Broadward Farm	29 April 2009	30 October 2012
River Lugg		
Site 3 - Eaton Hall Farm	09 August 2009	26 October 2012
Site 4 - Marlbrook Farm	21 September 2009	26 October 2012
Site 5 - Lugwardine	09 August 2009	30 October 2012

Each of the five monitoring sites was instrumented with Partech IR15C series optical turbidity probes to record suspended sediment information at 15 minute intervals over the duration of the study (Figure 3.4; Collins and Walling, 2004). The lenses of the optical turbidity sensors were cleaned regularly (Walling and Collins 2000), which was particularly important in summer months when algae growth was at its greatest. The turbidity data was stored in a battery-powered data logger, enabling a quasi-continuous record to be developed. According to Gippel (1989) the use of turbidity probes is suitable in suspended sediment research as discharge and sediment concentration are not always correlated. However, a variety of problems in deploying such probes and interpreting their output records have been identified. For example, optical turbidity probes are sensitive to ambient lighting conditions and the variation in particle shape, size and colour (Clifford *et al.,* 1995). It was therefore essential to cross-calibrate the probes between laboratory and field sampling over the period of study (Gippel 1989).

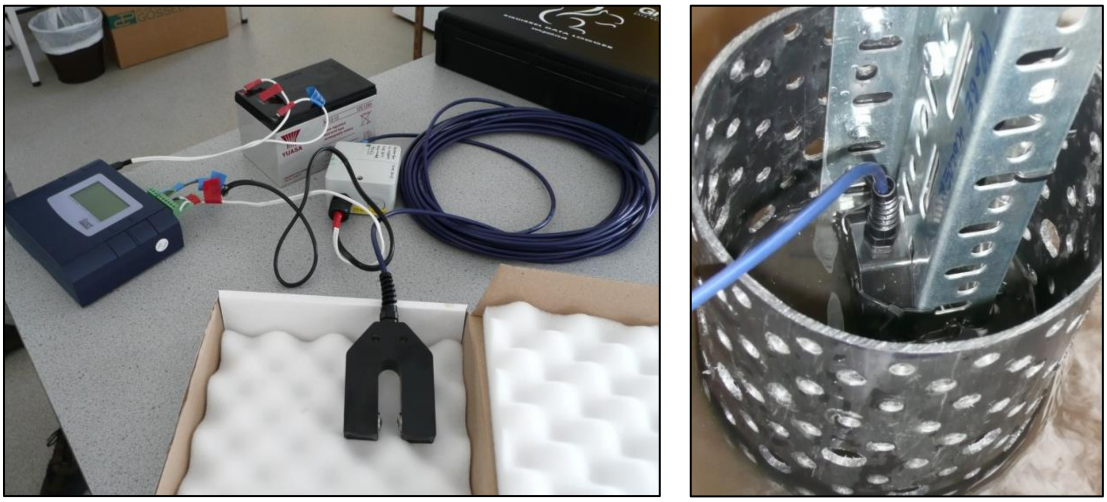


Figure 3.4 Turbidity probe and data logger set-up at each monitoring site.

The assumption that there exists a clear and unique relationship between measured turbidity values and the associated sediment concentration is fundamental to the success of this technique (Gao, 2008). Numerous studies have revealed that turbidity varies linearly with sediment concentrations of homogeneous size (Lewis, 1996). However, turbidity is sensitive to particle size and sediment composition (Gippel, 1989), and it has subsequently been discovered that particles of different sizes have different effects on turbidity given the same concentration (Gao, 2008). Consequently, the unique relationship between turbidity values and the associated suspended sediment concentrations may be unfounded, as variations in suspended load and grain size are typically heterogeneous at the catchment-scale (Riley, 1998). As a result, the obtained turbidity values may not be an appropriate surrogate for suspended sediment concentration (Gao, 2008).

It was therefore necessary to develop site-specific rating relationships for converting turbidity readings to actual suspended sediment concentrations (Collins and Walling 2004). An ISCO automated pumping sampler was utilised to sample suspended sediments during flood events (Figure 3.5). This uses an integrated pump to extract suspended sediment samples by an intake system programmed over a specific time interval (Gao 2008). For each monitoring location, samples were extracted from the channel, in the same vicinity as the turbidity probe to ensure comparability, into 1000 ml bottles. The sampler was deployed during storm events to capture peak suspended sediment concentrations, avoiding the tendency of suspended sediment load underestimation caused by infrequent sampling (Ferguson, 1986; Foster *et al.,* 1992).

Figure 3.5 The ISCO automated water samplers used to develop site-specific rating relationships.

To ensure the range of turbidity associated with the rise, peak and fall of high-magnitude events was captured, the sampling interval for each site accounted for the duration of the hydrograph, the physiographic condition of the particular catchment, and the location of the sampling sites (Lewis, 1996; Gao 2008). The extraction of suspended sediment samples is usually triggered by a pre-determined value of stage or flow velocity (Harmel *et al*., 2003; Lewis 2003). However, this device was not available during the period of study, so the samplers were deployed two or three times at each monitoring site, to ensure the sampler captured an appropriate range of turbidity values associated with the high-magnitude events.

The suspended sediment water samples were returned to the laboratory and processed using a filtration method outlined by Radojević and Bashkin (1999). Each water sample was filtered through pre-weighed Whatman grade 1 (11 µm) filter papers using vacuum filter apparatus. Filter papers were oven dried at 105 °C, cooled in desiccators to avoid the absorption of atmospheric water, and re-weighed. The concentration of suspended solids was determined from the increase in weight of the filter paper after filtration, using the following equation (Radojević and Bashkin, 1999):

$$SS = \frac{1000(Mt - Mb)}{V} \tag{4.1}$$

where: $SS =$ suspended sediment concentration in mg l^{-1}; $Mt =$ weight of the filter paper after sample filtration in mg; $Mb =$ weight of the filter paper prior to sample filtration in mg; $V =$ volume of the sample in ml.

Suspended sediment concentrations were consequently calculated through the development of site-specific calibration curves. These were constructed based on measured turbidity values determined at the time of suspended sediment sampling, enabling the conversion of raw turbidity values (mv) to suspended sediment concentrations (mg l^{-1}).

Hydrokit pressure transducers were installed at each of the five monitoring sites to record stage data at 15-minute intervals, coinciding with the turbidity readings, over the duration of the study (Figure 3.6). Pressure transducers were utilised in the research design due to their compact size, ease of deployment within the field, great accuracy (± 0.05%), and long internal battery life (~ 7 years), limiting the requirement of regular site visits. They were installed in the same vicinity as the turbidity probe to allow accurate relationships between turbidity and stage to be identified. Pressure transducers measure water pressure at a fixed point beneath the water surface; as water level increases during a flood, the pressure at the probe increases. This can be converted to stage or discharge once a rating relationship has been established.

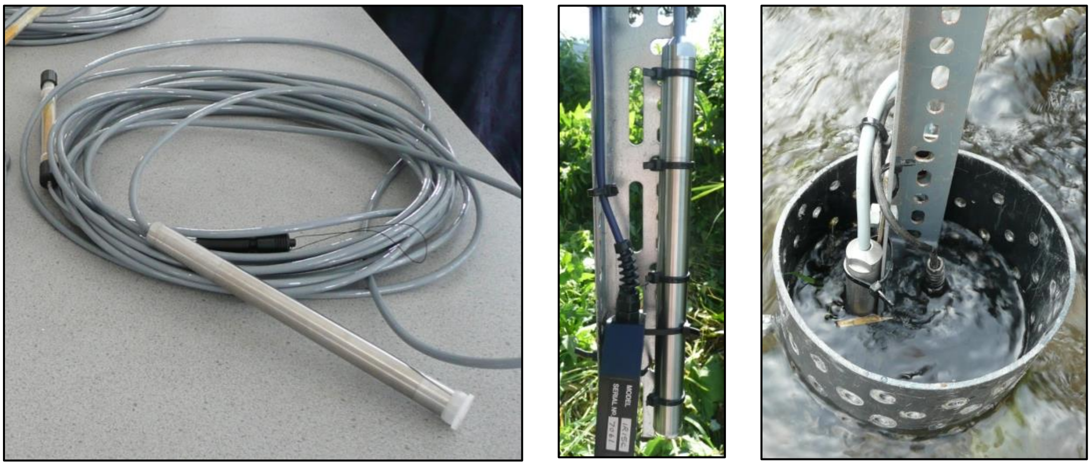
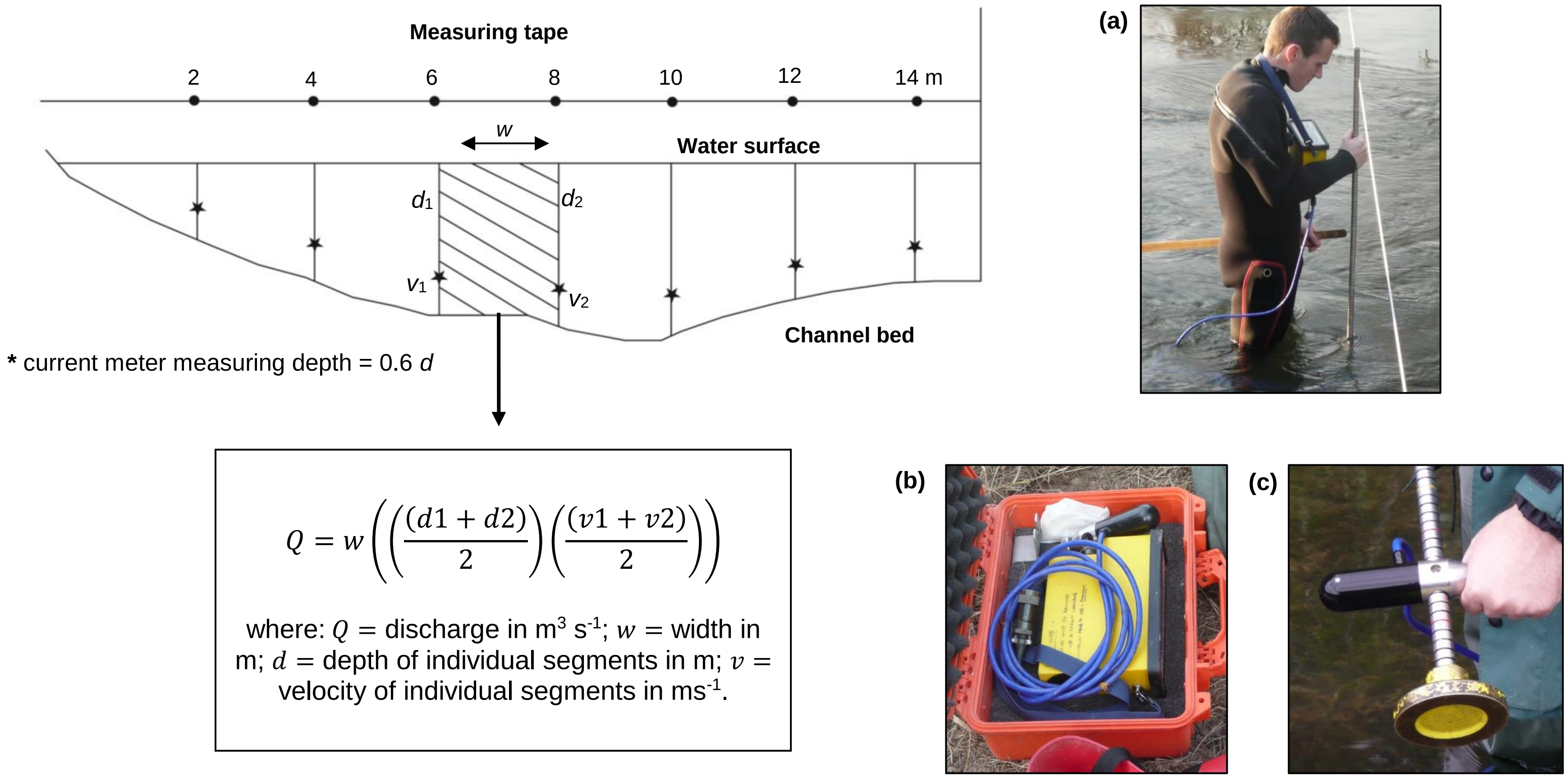


Figure 3.6 Pressure transducer installed at each monitoring site.

Cross-sectional velocity measurements were calculated over five different flow conditions, capturing a mixture of high and low flow events for each monitoring site. Surface velocity was measured using a Valeport Model 801 Electromagnetic Flow Meter, which has an accuracy level estimated at c. ± 0.5%. In order to generate site-specific rating relationships, a velocity-area method and ‘segmented approach’ (Goudie, 1994) was employed to convert the flow meter velocity readings into discharge (Figure 3.7). However, during periods of extreme flow conditions, the ‘float method’ (measuring the time it takes for buoyant objects such as sticks or logs to travel a specified distance downstream) was used to calculate surface velocity and discharge. This enabled site-specific spatio-temporal variations in discharge and suspended sediment to be identified over flood events of different magnitudes over the study’s period.



* current meter measuring depth = 0.6 *d*

$$Q = w\left(\left(\frac{(d1+d2)}{2}\right)\left(\frac{(v1+v2)}{2}\right)\right)$$

where: Q = discharge in $m^3\ s^{-1}$; w = width in m; d = depth of individual segments in m; v = velocity of individual segments in ms^{-1}.

Figure 3.7 Diagram and associated calculation of the velocity-area method used at each monitoring site (adapted from Goudie 1994) with pictures illustrating (a) the cross-sectional method; (b) the Valeport Model 801 Electromagnetic Flow Meter; (c) current meter measuring depth (Site 3 – Eaton Hall Farm 14th November 2012).

3.2.3 Field Sampling Approach

The field sampling approach developed for the sediment fingerprinting technique, employed in the catchment scale analysis, involved collecting a number of ‘sink’ samples, alongside potential source material, over the period of study. The following sections detail the sampling approach used in the catchment scale analysis phase.

Suspended Sediment Sampling

In order to identify the sources of fine sediment transfer within the Lugg catchment, suspended sediment samples were captured at each of the monitoring sites using time-integrating sediment traps (Figure 3.8). Laboratory trials have demonstrated a suspended sediment capture efficiency of between 31 and 71%, and a bias towards the coarser particles, with the smaller (< 2 µm) particles being expelled (Phillips *et al.,* 2000). Subsequent field tests have revealed a significant increase in the mass and grain size efficiency of the device, reflecting that much of the fine sediment transported in natural systems exists as aggregates or composite particles, rather than smaller discrete particles (Phillips and Walling, 1995). The field evaluation reported by Russell *et al.* (2000) confirmed that both the physical characteristics and the chemical composition of the sediment retained in the sampling device are like those of instantaneous manual samples collected during the same time period (Ballantine *et al.,* 2008). These devices are therefore capable of collecting representative samples of suspended sediment over different temporal scales (Walling *et al.,* 2008) and have been successfully used in numerous fluvial sediment sourcing studies (for example, Gruszowski *et al*., 2003; Evans *et al*., 2006; Walling *et al.,* 2006; Ballantine *et al*., 2008; Walling *et al*., 2008; Collins *et al.,* 2010c).

These samplers were deployed *in situ* in the river channel and utilised the reduction in the velocity of the ambient flow to encourage the deposition of suspended sediment within the main body of the sampler. The samplers were positioned in the channel and secured to a dexion frame, driven into the river bed. During deployment, the samplers were first filled with clean native water and then submerged in the channel, with the inlet tubes oriented directly into the flow (Phillips *et al.,* 2000). It has been acknowledged that these samplers should be installed at approximately 0.6 of the mean water depth (*cf*. Phillips *et al.,* 2001; Ballantine *et al.,* 2008). However, as water depth was highly variable throughout the study, it was difficult to ensure that the samplers were constantly installed at this depth. Therefore, the sampler position on the dexion frame was continuously altered depending on the flow conditions at the time of field visits. To reduce the effects of bed-load transport processes occurring during flood events, it was ensured that the sampler was situated at a sufficient height (generally around 15 cm) from the channel bed. Once submerged water entered the inlet tube continuously, where velocity was reduced by a factor in excess of 600 (Phillips *et al*., 2000; Ballantine *et al*., 2008; Walling *et al*., 2008). Sedimentation of the suspended sediment particles was thereby induced, as the water moved through the chamber towards the outlet tube.

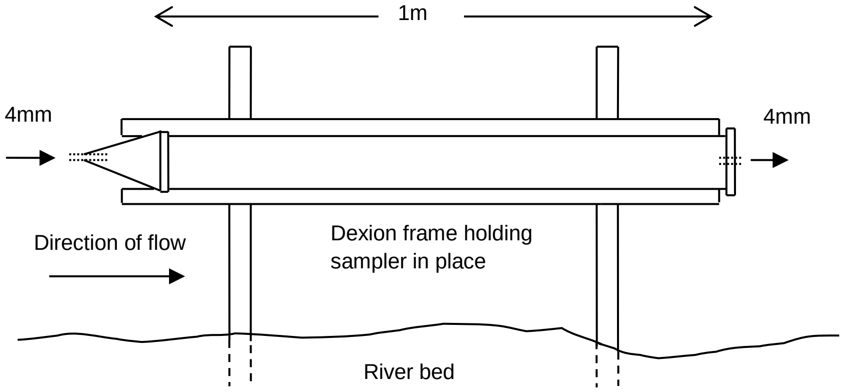


Figure 3.8 Time-integrated sediment sampler installed at each study site (based on Phillips *et al.,* 2000).

The samplers captured either individual storm events or a composite of different flood events, depending on the frequency of flood events over the period of study. Sample retrieval occurred approximately every 4-6 weeks over the period of study, or when particular flood event flows had subsided. This enabled suspended sediment to be sampled over a variety of different temporal scales. The samplers were disconnected from the uprights and completely removed from the channel during the retrieval. The contents were emptied into heavy-duty containers before being reinstalled in the channel (Figure 3.9).

Figure 3.9 The process of sample retrieval after flood events (Site 5 - Lugwardine 9th September 2010).

As sediment is transported from different parts of the catchment and is delivered through the catchment outlet at different times, ‘spot’ suspended sediment samples are unlikely to provide a representative indication of the overall sediment source contributions (Walling *et al*., 2008). Time-integrated samplers avoid this problem by sampling either a composite of multiple hydrograph events, or single events, depending upon sampling time and frequency (Ballantine *et al.,* 2008). The nature of their operation also prevents the logistical and practical problems associated with the need to visit sampling sites during high magnitude flood events and, therefore, ensures the sediment flux is continuously sampled.

Previous studies (e.g. Ballantine *et al*., 2008; Walling *et al*., 2008; Collins *et al.,* 2010c) installed a number of time-integrated sediment samplers at each site to ensure recovery of sufficient sample masses for subsequent analyses. However, owing to the high amounts of fine sediment transported within the Lugg catchment (Russell *et al.,* 2001), sufficient sample mass was collected at each monitoring site with just one sampler installed. Nevertheless, the installation of a replicate sampler at each of the monitoring sites, at a different height, was intended to overcome problems associated with the risk of sampler failure and accessibility issues during times when the flow was high.

Sediment transport is highly episodic, with the greatest suspended sediment loads being transported during high flows (Walling and Webb 1987; Lewis and Eads 2001). The use of the time-integrated sediment samplers at each site was therefore complemented by additional manual sampling on occasions when prolonged high flow conditions were experienced. This involved deploying astroturf mats (Lambert and Walling 1987) on the channel banks to capture the deposited suspended sediments during individual, high magnitude events (Figure 3.10). This sampling technique has been successfully used in overbank sedimentation studies, enabling individual storm events to be monitored and the deposited sediment to be readily recovered for subsequent analysis (*cf*. Simm and Walling, 1998; Owens and Walling, 2002; Walling and Owens, 2003). Sediment samples were retrieved from astroturf mats after the high magnitude events had receded by using a stainless-steel trowel and placing the sediment in a sample bag. The astroturf mats were then thoroughly cleaned to avoid sample contamination and replaced.

Figure 3.10 Manual ‘spot’ sampling over prolonged high flow events using astroturf mats (Site 3 – Eaton Hall Farm after flood event 6th-13th July 2012).

However, mats are highly susceptible to sample contamination via the splash of soil particles from the adjacent channel banks (Simm and Walling, 1998). This method was therefore only intended to complement the sampling strategy, providing a record of individual flood events during prolonged high flows, when access to the time-integrated samplers was problematic. A total of 138 suspended sediment samples were collected from the monitoring sites over the period of study, encompassing composite flood events from time-integrated samplers and individual high magnitude flow events from astroturf mats (Table 3.5).

Table 3.5 Total number of suspended sediment samples collected (138).

	Site 1 - Hunton Bridge	**Site 2 - Broadward Farm**	**Site 3 - Eaton Hall Farm**	**Site 4 - Marlbrook Farm**	**Site 5 - Lugwardine**	**Total**
Time-integrated samples	24	22	22	19	18	**105**
Astroturf mat samples	2	9	10	2	10	**33**

Gravel Substrate Sampling

It was essential to obtain information concerning the concentration of fine sediment (< 2 mm) within gravel substrate voids in order to assess the quality of the substrate gravels at each monitoring site. There are limited amounts of research in the literature indicating that the infiltration of fine sediment into river bed interstices is intimately linked to the concentration of suspended sediment (Frostick *et al.,* 1984; Huang and García, 2000). It was therefore necessary to complement the suspended sediment collection via the time-integrated samplers, with the assessment of surface and subsurface grain-size characteristics. This process was conducted at each monitoring site once to establish baseline grain-size distribution of the subsurface gravels and fine sediment loadings. The fine sediment was analysed for metal content and consequently used as ‘sink’ samples to determine sediment provenance of the substrate material.

The grain size of surface sediments at each monitoring site was assessed by using the Wolman pebble count method (Wolman, 1954). A transect was placed across the river channel at each site, where the intermediate axis of 100 individual clasts from the bed was measured. Clasts were drawn from the armour layer on a random basis, to ensure a representative analysis of the surface material. The intermediate axis of each clast was measured as it represents the grain size that would pass through a sieve with an aperture of an equivalent diameter. This enabled comparisons to be made with the subsurface material, which was sampled using a different method, and subsequently sieved.

A freeze-coring technique using liquid Nitrogen was utilised to assess the subsurface grain size distribution at each monitoring site (Stocker and Williams, 1972; Pugsley and Hynes, 1983; Milan, 1994; 1996; Evans and Wilcox, 2013). This method allows relatively undisturbed vertical sections of the channel bed to be removed without losing fine-grained material, which is a common problem in using bulk samples to assess gravel-bed substrate (Milan *et al.,* 2000; Zimmerman *et al*., 2005). However, the insertion of standpipes into the channel bed may physically disrupt the stratification of sediments by displacing the finer particles (Beschta and Jackson 1979). Nevertheless, this technique has subsequently been successfully employed in a number of studies to assess macroinvertebrate habitat and quality of fish spawning grounds (Crisp and Carling, 1989; Scrivener and Brownlee 1989; Kondolf 1988; Payne and Lapointe 1997; Milan *et al.,* 2000), to monitor changes in gravel substrate (Petts and Thoms 1986; Thoms, 1987; Petts *et al.,* 1989; Rood and Church, 1994; Spillos and Rothwell, 1998) and to develop sediment sampling recommendations (Milan *et al*., 1999).

The freeze-coring design methodology proposed by Milan (1996) was utilised to sample sub-surface bed sediments up to a maximum depth of 60 cm (Milan *et al.,* 1999) at each monitoring site (Figure 3.11). For the purpose of this research, cores were taken to a depth of 30-40 cm below the bed surface. This depth is ecologically-important, as spawning salmonids lay their eggs in excavated redds at this depth before they are subsequently buried under bed material (Lisle, 1989; Petts *et al*., 1989). This zone, where the matrix material has been selectively winnowed, is notably more susceptible to deep fine sediment infiltration through the gravel voids. However, the size of the fine sediment relative to the size of the bed material can affect the depth to which fine sediment can infiltrate a gravel bed (Einstein, 1968; Carling, 1984; Diplas and Parker, 1985; Lisle, 1989). Immediately after the redd formation, fine sediment can infiltrate gravel voids and settle at this depth, gradually filling bed material pores upwards (Einstein, 1968) until subsequent rising stages cause the entrainment of the armour layer. Sand particles can then become trapped in the interstices of the top several centimetres, forming a near-surface seal and consequently inhibiting further infiltration of fine sediment (Beschta and Jackson 1979; Lisle 1989). As a result, fine sediment will only infiltrate down to a limited depth (Carling 1984; Schälchli 1992). It was therefore important that the cores were taken to a depth where salmonids lay their eggs, in order to assess the quality of the substrate material at each monitoring site.

The design included pounding hollow steel standpipes with a closed driving point at one end into the river-bed to a depth of 30-40cm at each sampling site. Approximately 6-10 litres of liquid Nitrogen was slowly poured into the standpipes continuously over a 20-25 minute period while the surrounding substrate was frozen to the standpipe. This ensured that the bottom 30-40 cm of the standpipe constantly had liquid Nitrogen present over the whole sampling period, while it boiled and vaporised. The amount of liquid Nitrogen used and the freezing time for each core was dependent upon water temperature and interstitial water velocity (Thoms, 1992), along with gravel permeability (Barnard and McBain 1994) that can affect the freezing efficiency. Owing to the differential freezing of particles, larger clasts are easily frozen to the exterior of the core sample (Adams and Beschta, 1980; Lisle and Eads, 1991). It was therefore important that enough liquid Nitrogen was used over an adequate time-frame to ensure that the finer particles were sampled. A frozen columnar core of substrate was formed around the outside of the standpipe which was retrieved using a tripod, manufactured by T. Booth Engineering Ltd with a safe working weight of 1000 kg, and an ACE 750 kg ratchet lever hoist (Figure 3.11). Upon retrieval, the cores were placed on a tray, then measured and sectioned into upper 15 cm and lower 15 cm intervals to provide information on the vertical variability in grain-size distribution (Milan, 1996; Milan *et al.,* 1999). Depths of 15 cm have been found to reduce errors in sub-dividing cores to determine sediment profiles (Milan *et al.,* 2000).

The size distribution of channel bed material is highly variable across a channel (Mosley and Tindale, 1985). As a result, representative determinations of fine sediment concentration and grain size distribution within gravel substrates required five cores to be sampled from undisturbed gravels across a riffle cross-section at each monitoring site (Thoms, 1992; Hughes *et al*., 1995; Milan *at al*., 2000). However, the size of individual cores sampled using this technique is usually too small to accurately represent the particle size distribution of the substrate (Lisle and Eads, 1991; Rood and Church, 1994). Nevertheless, as the site-specific spatial variability of sediment properties was not of interest the upper 15 cm and lower 15 cm sections of the five individual cores at each sampling site were amalgamated to assess the overall mean grain-size distribution (Wolcott and Church, 1991; Milan *et al*., 1999). It has been recommended that these bulk samples should yield a minimum acceptable composite wet weight of 20 kg, assuming a 5% sampling error at the 95% confidence level (Church *et al*., 1987; Thoms, 1987; 1992; Milan *et al.,* 1999). It was therefore critical that the upper 15 cm and lower 15 cm core sections for each sampling site comprised a mass of at least 20 kg (Petts *et al.,* 1989; Milan 1996; Milan *et al.,* 2000).

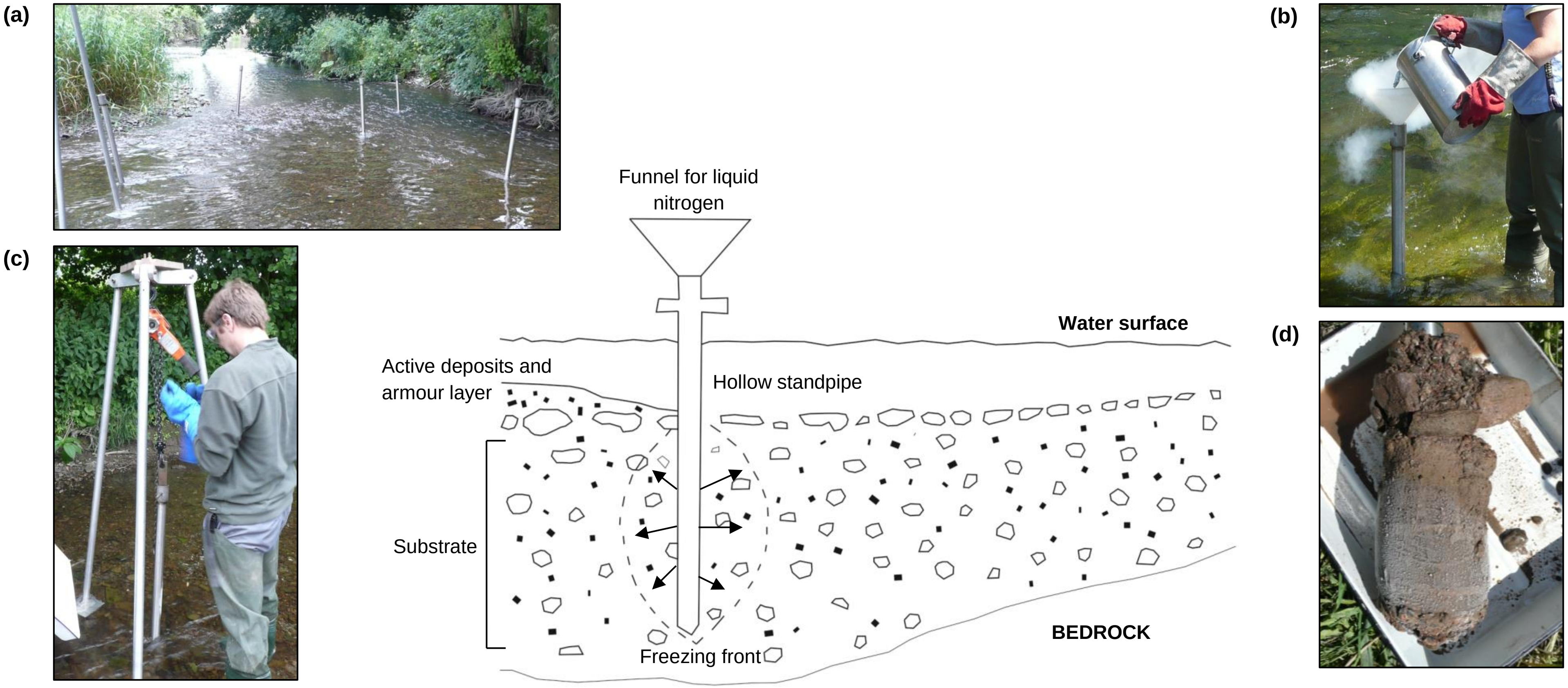


Figure 3.11 Diagram of the freeze-core process (based on Milan 1996) showing (a) the location of standpipes across a channel cross-section at each site; (b) the process of slowly pouring liquid Nitrogen into the hollow standpipes; (c) the procedure of removing the freeze core using a tripod and winch system; (d) the frozen substrate core (Site 1 - Hunton Bridge 10th July 2010).

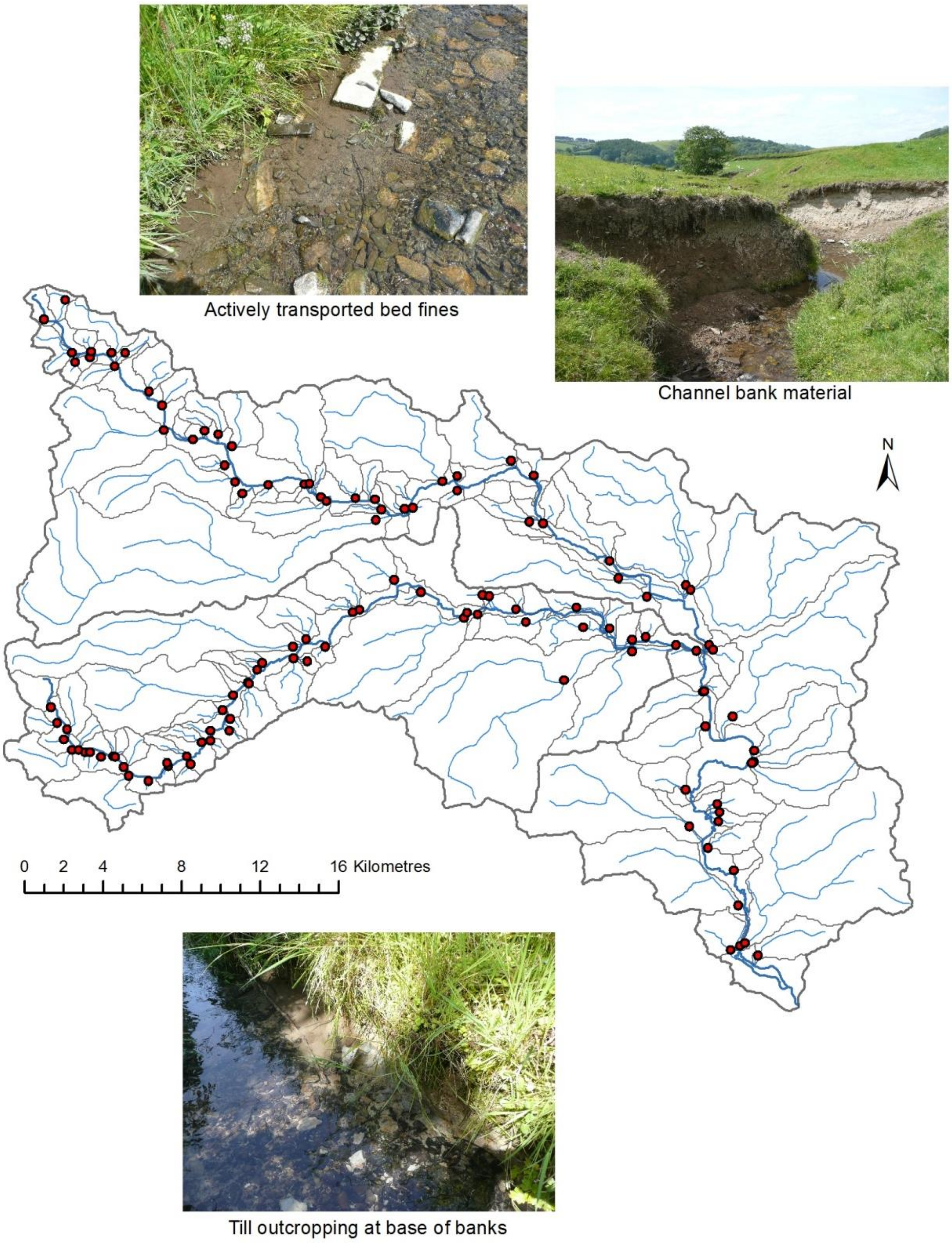
Source Material Sampling

Many previous sediment sourcing studies have been focused upon source types derived from surface and subsurface sources, such as topsoils from areas of different land use management practices and channel banks (Walling and Woodward, 1995; Collins *et al.,* 1997c; Walling and Amos, 1999; Walling *et al.,* 1999a; Owens *et al.,* 2000; Walling 2005; Minella *et al.,* 2008; Walling *et al.,* 2008; Collins *et al.,* 2010b; 2010c; 2012). However, in catchments that are larger than 500 km^2 where the number and complexity of sources is substantial (Collins and Walling 2004), it is more practical to address provenance based on distinct pedological or geological zones, or different tributary sub-catchments (Caitcheon, 1993; Walling and Woodward, 1995; Collins *et al*., 1996; 1997a; 1998; Botrill *et al.,* 2000; Owens *et al.,* 2000; Walling *et al*., 2008). During this catchment-scale analysis phase, collection of representative source material samples was therefore stratified to encompass all tributary sub-catchments converging with the mainstem Lugg and Arrow channels.

The rationale of selecting sub-catchments utilised an intensive field reconnaissance programme which was integrated with a nested systematic and stratified sampling strategy. Between September 2010 and July 2011, 120 tributary sub-catchment outlets were sampled (Figure 3.12). From each outlet location, source samples were taken from actively transported fine material on the bed surface, channel bank material and, where evident, till outcropping at the base of banks (Table 3.6). The total number of samples collected was 275.

Table 3.6 Total number of potential source samples collected (275).

	River Lugg (1077 km^2)	**River Arrow (290 km^2)**	**Total**
Bed samples	73	54	127
Bank samples	72	53	125
Till samples	11	12	23



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Pictures taken during field reconnaissance, June 2011

Figure 3.12 Location of samples taken from tributary outlets in the catchment.

Surficial fine material on the channel bed, assumed to reflect deposits from the most recent flood events, at each sub-catchment outlet was sampled on one occasion. The fine sediment was sampled to a depth of 0-3 cm, since this material is readily entrained and deposited by varying flow conditions (Stutter *et* *al*., 2009). Even though this technique failed to provide a temporal control, it has been recognised that constant remobilisation of fine bed sediment continuously occurs within a channel (Collins and Walling, 2006). Therefore, each channel bed source sample comprised a composite of small bed scrapes (Collins *et al*., 2010a) taken from approximately five different areas at each outlet to increase the representativeness of the sample and prevent any potential bias associated with sample location. Although the use of bed sediment traps (Carling 1984; Lisle and Eads, 1991; Sear, 1993; Acornley and Sear, 1999; Walling *et al*., 2003; Lachance and Dube, 2004; Zimmermann and Lapointe, 2005) would have provided a more reliable means of collecting fine bed sediment samples at each outlet, the temporal and financial demands associated with deploying such traps over a large catchment excluded their use in this study. Channel bank sediment comprised material from the full vertical extent of the bank profiles (Walling *et al*., 2008; Collins *et al*., 2010a) at each sub-catchment outlet. This sediment was representative of the past legacy of supra-bank sedimentation during past flood events. However, at a small number of sub-catchment outlets, a clay-rich till unit was visible at the base of the channel bank profile (Figure 3.13), representing the past glacial re-working of sediments. This layer was different in colour in various parts of the catchment; for example, in the upper part of the catchment this layer had a grey-like colour, whereas in the lower parts it reflected the underlying Old Red Sandstone geology and exhibited a reddish colour.

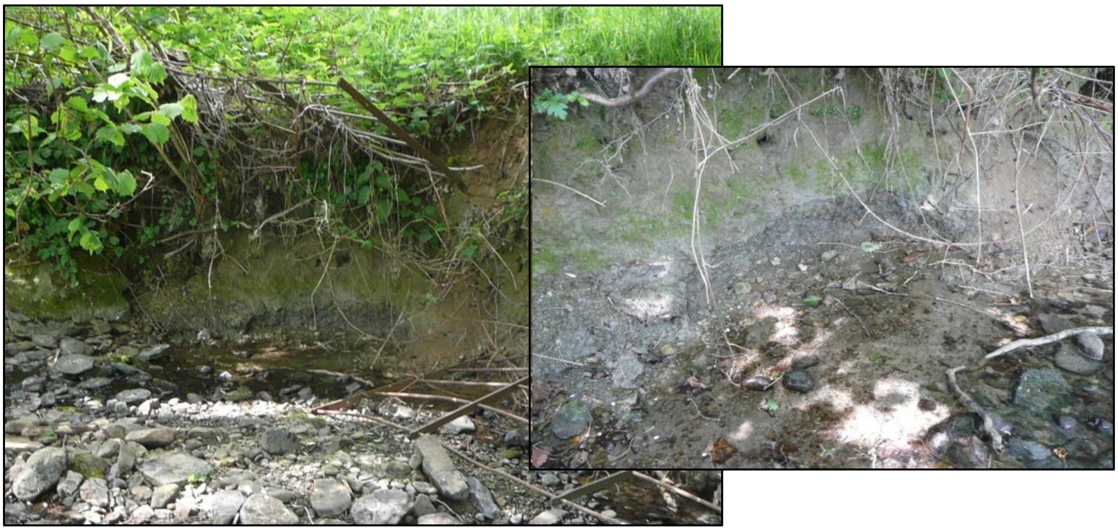

Figure 3.13 Till outcropping evident at the base of channel banks at particular sub-catchment outlets (Gladestry Brook, River Arrow, 19th May 2011).

Where outcropping was evident, an additional sample was collected from this base layer, which contained a lithological mixture of local and regional sources. In order to allow subsequent laboratory analyses to take place, an efficient sample weight of 500 g was taken from each source material using a non-metallic trowel, which was cleaned after each sample to avoid inter-sample contamination.

3.3 Sub-Catchment Scale Analysis

3.3.1 Sub-Catchment Selection

From an environmental management perspective, it is important to reliably pinpoint specific sources of fine sediment delivery based on catchment surfaces comprising different land uses. This is relatively difficult to do at the catchment scale, where there is great intensity in the number and spatial complexity of sediment sources (Collins and Walling 2004). Therefore, within the Lugg catchment, a more detailed sampling and field reconnaissance strategy was developed in sub-catchments that were determined to be important contributors of fine sediment. Important sub-catchments were determined from the catchment-scale sediment source analysis from the first phase of data collection and were estimated to consistently deliver sediment contributions of greater than 10% to the monitoring sites. Most of these sub-catchments have been identified as being at risk from diffuse pressures through other studies in the Lugg catchment, for example, the Rural Sediment Tracing Report (APEM, 2010) and wet weather sediment mobilisation and delivery studies (Environment Agency, 2006; McEwen *et al.,* 2011).

Through consideration with the Project Advisory Group, the important sub-catchments that required further investigation were identified. Sub-catchments where sources of fine sediment have already been recognised, for example the Stretford Brook (Walling *et al.,* 2008), were deemed to be less important and were therefore removed from consideration. Furthermore, sub-catchments that had impacts on only a limited number of monitoring stations owing to their catchment location, for example the Little Lugg (located in the lower reaches of the catchment and only impacting on one monitoring site), were also excluded.

As a result, a total of four sub-catchments were identified as requiring further investigation in order to identify the sources of fine sediment. These sub-catchments were identified as Cheaton and Ridgemoor Brooks, draining into the River Lugg and Curl and Moor Brooks, draining into the River Arrow (Figure 3.14). These four sub-catchments were treated as sediment 'sink' sites, where a detailed sediment source fingerprinting approach was adopted to identify specific sources of fine sediment.

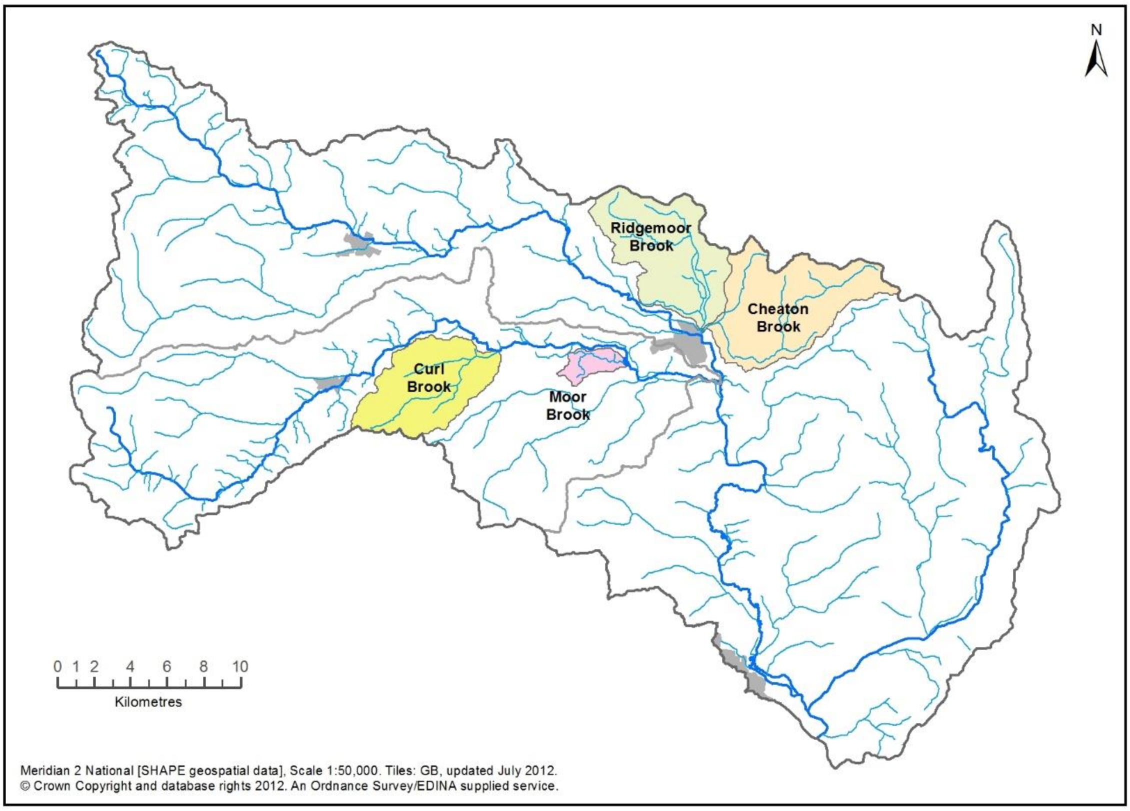

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Figure 3.14 The location of the four sub-catchments selected for the sub-catchment scale sediment sourcing study.

3.3.2 Suspended Sediment and Source Material Sampling

For effective sediment management and mitigation strategies to be implemented, reliable information on the sources of fine sediment is required (Collins *et al*., 2009; 2010a). It has been acknowledged that increasing siltation risk is due to changes in catchment land-use and poor agricultural practice (Theurer *et al.,* 1998; Naden *et al.,* 2003). It was therefore important that the sediment sourcing exercise within the four sub-catchments aimed to assemble information on the contributions of fine sediment by land-use. Through discussions with the Project Advisory Group, the sub-catchment scale analysis was designed to provide catchment managers with sediment source data to help target advice and mitigation planning within the four sub-catchments. These were identified through the original catchment-scale study, as contributing high levels of fine sediment to key sites within the Lugg catchment.

To evaluate the relationship between specific land-use types and sediment delivery, fine suspended sediment samples were collected after flood events using the same time-integrated sediment samplers used in the first phase of data collection. These were installed at each of the four sub-catchment outlets, sampling individual storm events between March and November 2012. This time-frame was considered sufficient to capture a number of different storm events and coincide with the main agricultural phases in the catchment (for example, potato and crop harvesting, livestock grazing and the construction of polytunnels). During this period, a total of 35 time-integrated suspended sediment samples were collected from the four sub-catchments (Table 3.7).

Table 3.7 Total number of suspended sediment samples (35) collected from the four sub-catchments.

	Cheaton Brook (39 km^2)	**Ridgemoor Brook (35 km^2)**	**Curl Brook (28 km^2)**	**Moor Brook (4 km^2)**
Suspended sediment samples	9	8	9	9

The sediment source sampling procedure adopted in each sub-catchment was stratified to focus upon source types derived from catchment surfaces of different land-use types and subsurface sources. This enabled the identification of the relative effects of natural and anthropogenic influences on land surfaces. Following an intensive review of the available literature, an assessment of the local land-use of the individual sub-catchments (Figure 3.15), and discussions with the Stakeholder Advisory Group, five primary source types were identified for sampling; provenance was classified by pasture, arable and woodland topsoils, channel banks and farm track surfaces (Figure 3.16). However, during field reconnaissance it was evident that woodland was particularly limited in the Ridgemoor and Moor Brook sub-catchments. These woodlands exhibited very low connectivity with the channel network and no evidence of recent fine sediment mobilisation and surface erosion. Consequently, it was decided that woodland samples would be omitted from the research design within the Ridgemoor and Moor Brook sub-catchments.

Previous research has also identified additional important secondary source types, such as metalled road surfaces (Gruszowski *et al.,* 2003). However, this source type is a secondary source of suspended sediment transporting sediment derived from the erosion of topsoils to the river network. It was therefore decided that road surfaces would not be included in the sampling strategy. Nevertheless, unmetalled farm track surfaces have been identified as major primary sources of sediment in rural catchments (*cf*. Ziegler *et al.,* 2000; Wemple *et al*., 2001; Collins *et al*., 2010c; 2012a). Consequently, this source type was incorporated into the research design owing to the agricultural nature of the Lugg catchment. Hopyards have also been identified as an important source of sediment (Russel *et al.,* 2001; Hodgkinson and Withers, 2007). Hop growing is mainly concentrated in the lower parts of the Lugg and Frome catchments. Field reconnaissance revealed that hopyards were not common in the four sub-catchments and therefore it was not necessary to include these in the sampling design. Furthermore, field drains have been identified as being a significant secondary source of suspended sediment (Kronvang *et al.,* 1997; Russell *et al*., 2001; Chapman *et al*., 2005; Heathwaite *et al*., 2006). However, the drainage network in the Lugg catchment is fragmented with no reliable evidence of where field drains are located. Therefore, the timescales involved for field walking and identifying these rendered their incorporation in the research design impractical. Furthermore, the identification of catchment sources involved the Project Advisory Group, who were concerned with surface soil erosion and runoff in the catchment. It was therefore decided that the source sampling strategy would target surface soils under different land practices and as a result, field drains were not included in the sampling approach. Given the agricultural nature of the Lugg catchment, this omission could exclude an important delivery pathway of sediment and potentially suppress relative contributions delivered from agricultural topsoils. Therefore, this should be considered when interpreting the sediment sourcing results.

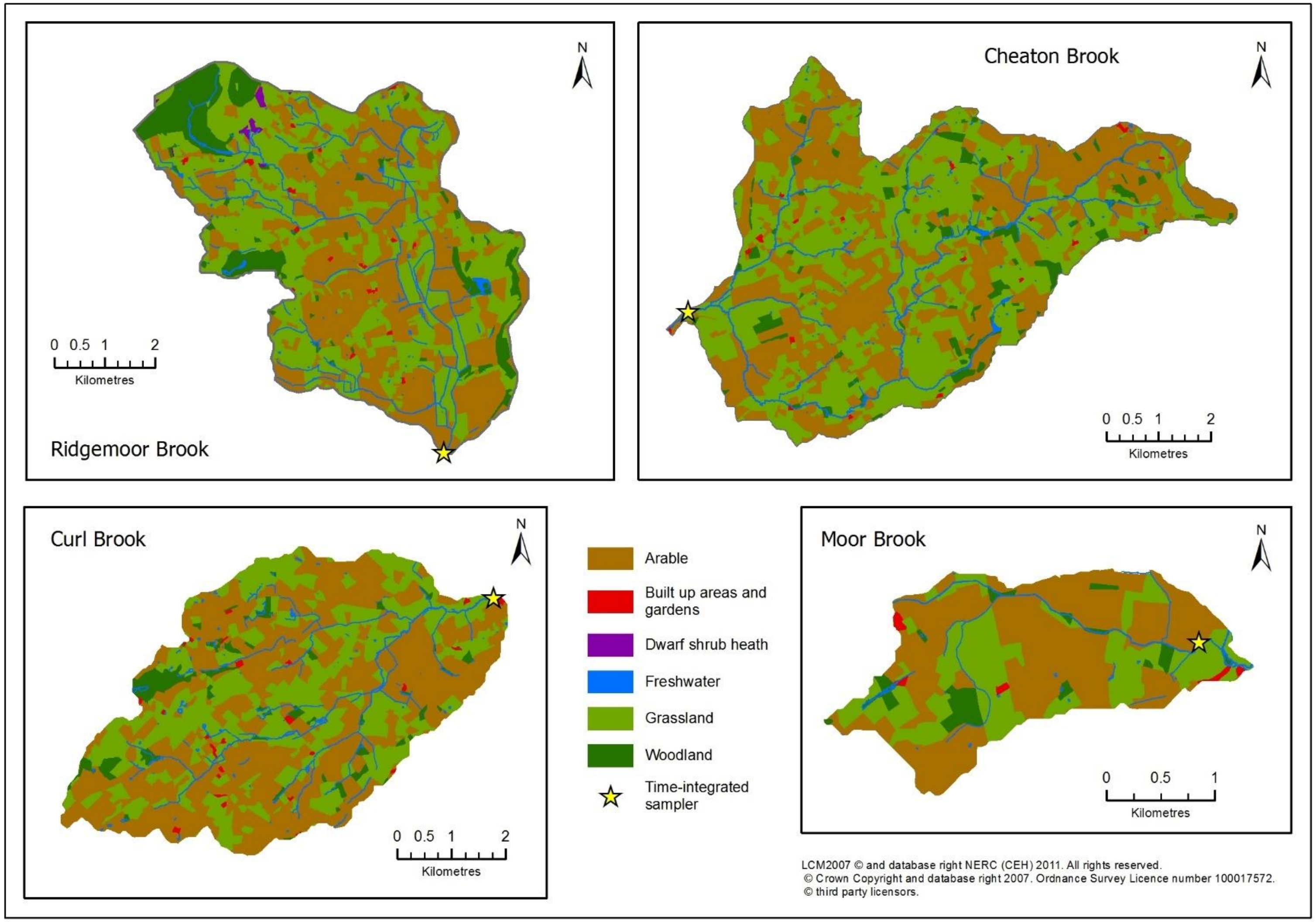

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Figure 3.15 Land cover maps for the four sub-catchments selected for the sub-catchment scale sediment sourcing study.

Figure 3.16 Examples of the five source types sampled at each sub-catchment.

The sub-catchment sampling procedure occurred between July and September 2012. A total of 249 potential sediment source samples were taken from these primary source types (Table 3.8). The samples of potential source material were retrieved using a stainless-steel trowel, which was repeatedly cleaned to avoid inter-sample contamination. A representative sample from surface topsoils and farm tracks was obtained from surface scrapes of the uppermost layer (0-5 cm depth), most susceptible to mobilisation by rainsplash and water erosion. Topsoil surface samples were subsequently taken from areas exhibiting high connectivity and the potential to deliver fine sediment to the river network. Sediment collection from farm tracks comprised material from surfaces and verges where vehicle traffic or livestock trampling had caused severe surface degradation (Collins *et al.,* 2010b). Channel bank sediment collection encompassed material from the full vertical extent of exposed, actively-eroding channel bank sections. In order to avoid over-representation of the topsoil surface, particular emphasis was concentrated on the lower horizons of the profile (Collins *et al.,* 2010c). Each potential source sample comprised a composite of 5-10 smaller scrapes collected in the vicinity of the sampling point to increase the heterogenic representativeness of the individual sources and of the overall sampling strategy (Minella *et al*., 2008; Collins *et al.,* 2012). Replicate composite samples, relatively even in distribution across each sub-catchment (Figures 3.17a-d), were also collected from each source type to encompass geological and pedological variability and to avoid any potential bias (Collins *et al*., 2010a).

Table 3.8 Total number of potential source material samples (249) collected from the four sub-catchments.

Source Type	**Cheaton Brook ($39\ km^2$)**	**Ridgemoor Brook ($35\ km^2$)**	**Curl Brook ($28\ km^2$)**	**Moor Brook ($4\ km^2$)**
Pasture topsoils (grassland)	22	20	16	7
Cultivated topsoils (arable)	14	18	19	7
Woodland topsoils	10	N/A	11	N/A
Channel banks	24	13	18	8
Farm tracks	14	10	12	6
Total	**84**	**61**	**76**	**28**

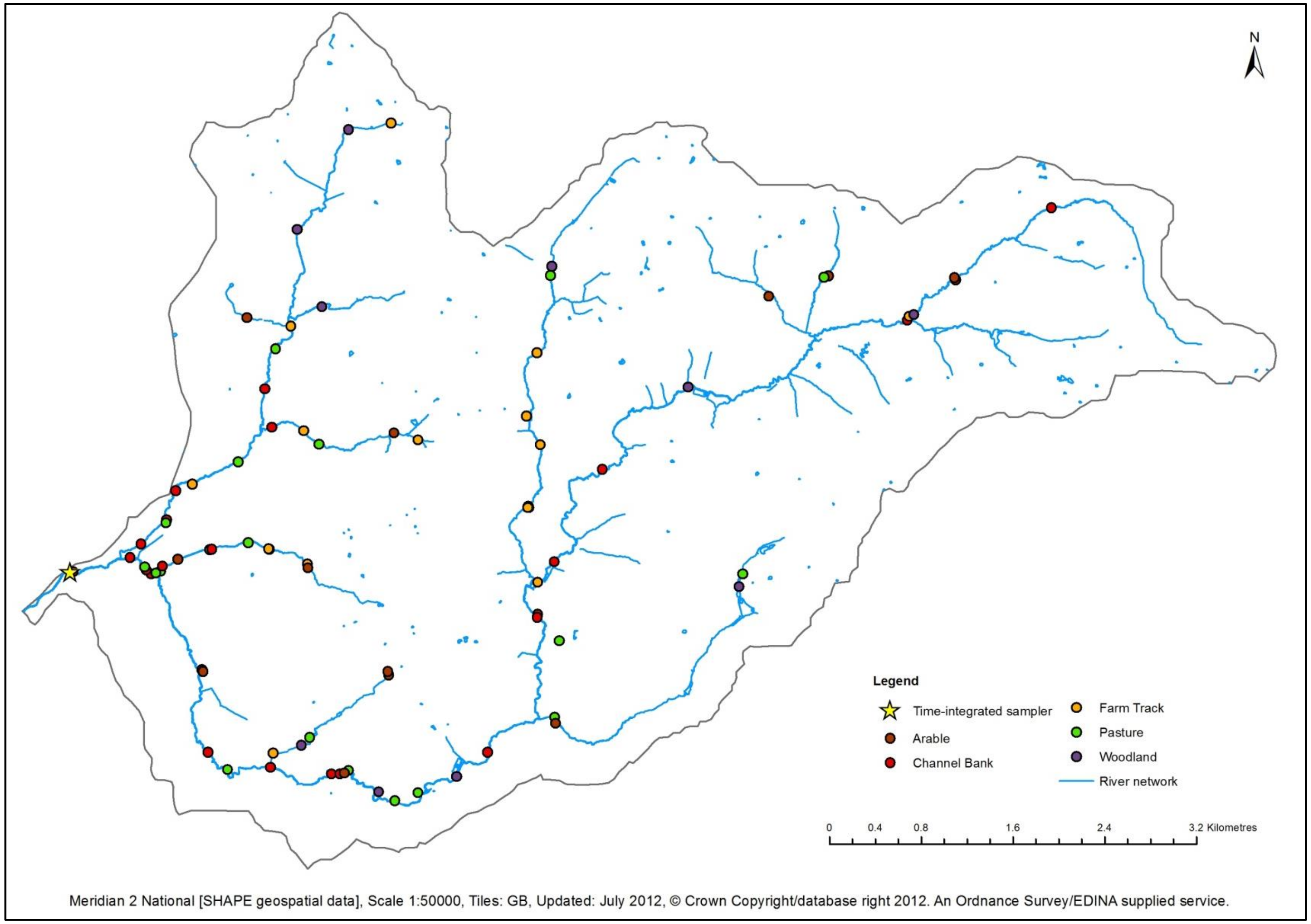

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Figure 3.17a Distribution of potential sediment source sample points in the Cheaton Brook catchment

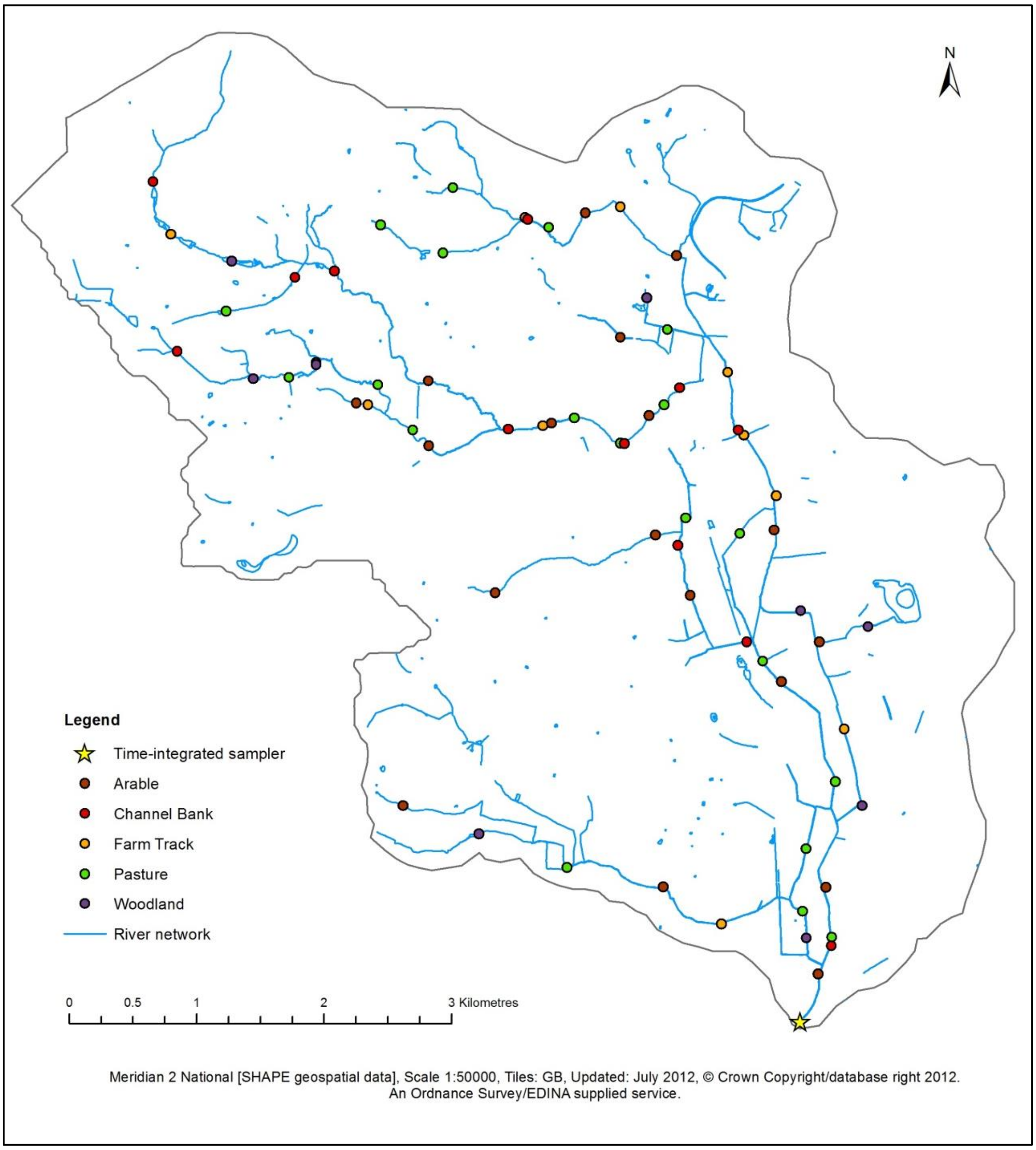

Figure 3.17b Distribution of potential sediment source sample points in the Ridgemoor Brook catchment.

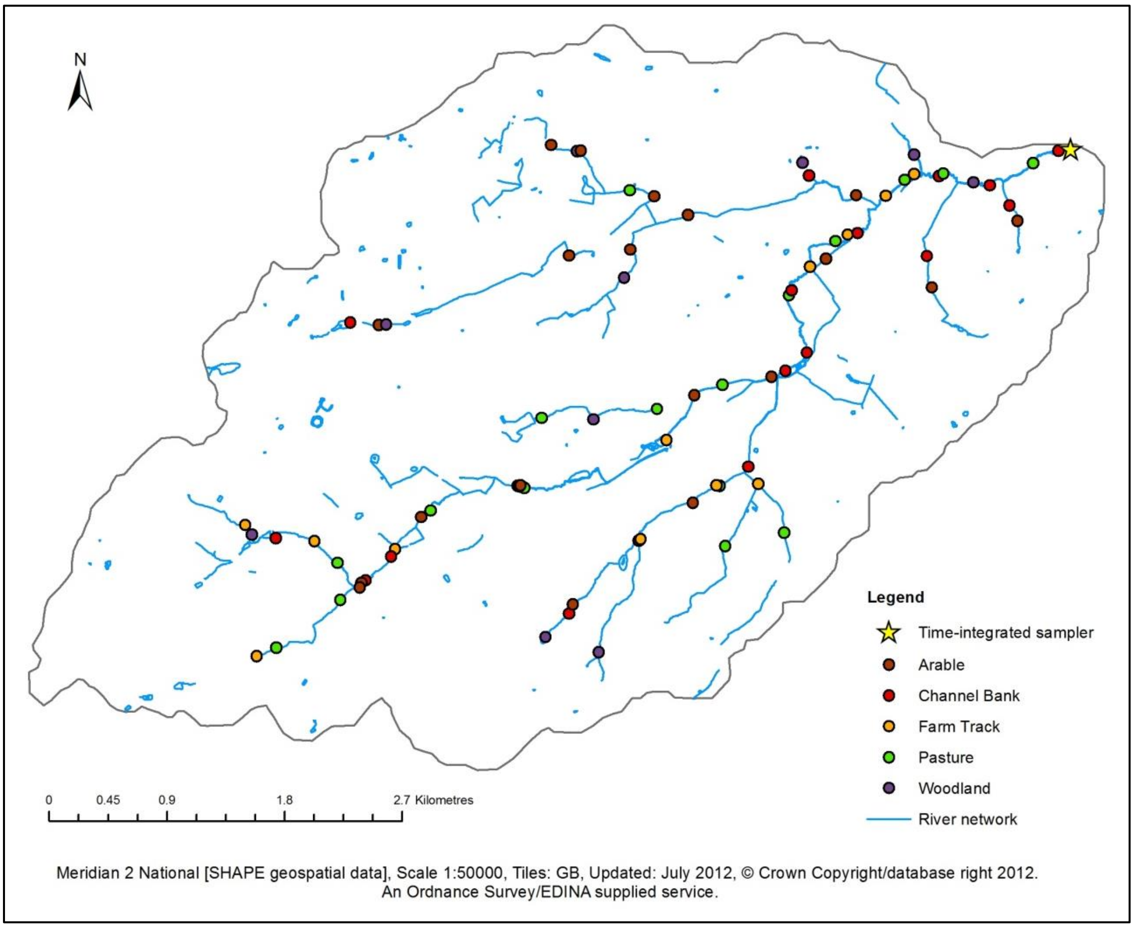

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Figure 3.17c Distribution of potential sediment source sample points in the Curl Brook catchment.

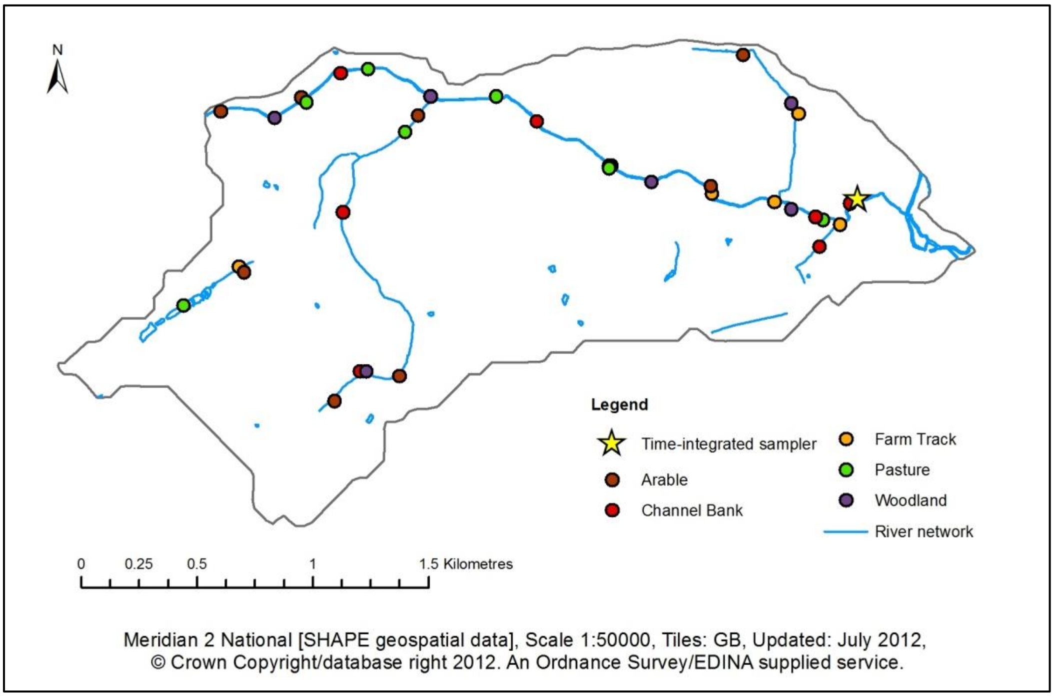

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Figure 3.17d Distribution of potential sediment source sample points in the Moor Brook catchment.

3.4 Laboratory Preparation and Analytical Procedures

All suspended sediment samples and potential source material collected at the macro and meso-scale were returned to the laboratory, oven-dried at 40 °C over a 48-hour period, and gently disaggregated using a pestle and mortar (Gruszowski *et al.,* 2003; Walling *et al.* 2008; Collins *et al.,* 2010b). Dried samples were passed through a set of nested sieves using an automatic shaker over a standardised time period to ensure sample consistency. Samples that consisted of a high percentage of clay material were wet sieved to aid successful disaggregation. Each size fraction was weighed to give a full assemblage of grain-size distribution categories, with the <1 mm material retained for subsequent analyses, which are detailed in the following sub-sections.

3.4.1 Grain Size Analysis

Information on particle size is of fundamental importance in understanding and modelling the entrainment, transport and deposition of fine sediment (Bui *et al*., 1990; Walling *et al.,* 2000; Blott and Pye 2001). Many studies have identified that grain size distributions of eroded and transported sediments significantly influence element property concentrations, which in turn can affect the determination of sediment provenance (Horowitz and Elrick, 1987; Walling and Morehead, 1989; Horowitz, 1991; He and Walling, 1996; Foster *et al.,* 1998; Walling *et al*., 1999b; 2000; Ranasinghe *et al.,* 2002; Motha *et al.,* 2002; Zhang *et al*., 2002; Stutter *et al*., 2009; Bloemsma *et al.,* 2012). Therefore, it is possible that issues could arise when comparing properties of suspended sediment samples and potential source material owing to the variation in grain size composition. In order to limit the influence of this grain size effect, all samples were sieved through a 1 mm mesh to enable direct comparisons between the sink and source material. Previous studies (*cf*. Collins and Walling, 2002; Walling *et al* 2008; Owens *et al*.,1999; Collins *et al*., 2010b; 2012) have used the <63 µm fraction, which is recognised as the dominant grain size of suspended sediment carried by most rivers (Walling and Moorehead, 1989; Phillips and Walling, 1999; Walling *et al*., 2000). However, it is important to ensure that the grain size distribution of the source material is similar to that of the sediment sampled. For example, using synthetic and field data from ongoing sediment provenance studies in Ireland, Sherriff *et al*. (2015) found that suspended sediment samples were frequently coarser than this dominant grain size and therefore, it was necessary to include the >63 µm fraction in the analysis. Owing to the easily erodible fine sandy soils, the River Lugg and its main tributaries have a natural propensity for coarser suspended sediment loadings during high magnitude events (Gruszowski *et al.*, 2003). Particles exceeding medium-coarse sand in size (0.5-1 mm) are therefore likely to be transported during these events (Regüés and Nadal-Romero, 2013) due to a positive relationship between an increase in suspended sediment concentration and particle size (Frostick *et al.,* 1983; Long and Qian, 1986; Reid and Frostick 1987; Xu 1999). Consequently, it was important to provide representative analysis of the potential particle sizes transported over a variety of different flood magnitudes. Research has also found that these sand-sized particles can be harmful to fish embryo success. For example, Beschta and Jackson (1979) demonstrated these coarser sand particles can block interstitial pore spaces forming a near-surface ‘seal’, rather than settling at depth. This can encourage entombment, impeding the alevin swim-up phase (Olsson and Persson 1988). It was therefore essential that 63 µm – 1mm particles were included in the research analysis.

Owing to the influence of grain size on elemental property concentrations, it was important to determine the absolute particle size distribution of the <1 mm material from all suspended sediment and potential source samples collected within the catchment. A variety of analytical techniques are available for the determination of particle size distribution, including laser diffraction, photon correlation spectrometry, sedimentation, image analysis and acoustic spectrometry. Goossens (2008) determined that, for suspended sediment laser diffraction was the most effective particle-sizing technique. The laser diffraction method can cause an underestimation in the clay fraction owing to the assumption of equivalent particle sphericity. For example, irregular shaped particles can become assigned to a larger size fraction if they exhibit a cross-sectional area greater than that of a sphere, while having the same volume (Di Stefano *et al.,* 2011). Nevertheless, this technique can provide a much higher resolution of the particle size distribution, as it enables the determination and analysis of smaller particle sizes compared to other techniques (Bittelli *et al.,* 1999). It can also automatically estimate specific surface area (SSA) based on cumulative size distributions, which is important to facilitate direct comparisons between the source material and the potentially finer suspended sediment samples. A Malvern Mastersizer 2000 Laser Granulometer was used to determine particle size distributions throughout this study. It has been designed to efficiently measure particle sizes ranging from 0.02 to 2000 µm over a short period of time with high precision ± 5% (Sperazza *et al.,* 2004; Di Stefano *et al.,* 2010; Storti and Balsamo, 2010).

Prior to the particle size analysis, all samples were sub-sampled using riffling, coning and quartering methods (Mullins and Hutchison, 1982) to eliminate heterogeneity within the sample and to reduce sample size to 4-5 g. It was important to concentrate on the <1 mm material since laser diffraction carries a high risk of under-representativeness when measuring grains >1 mm (Dinis and Castilho 2012). This is especially the case when there are high amounts of clay-silt particles present in the majority of the samples.

The sub-sampled material was pre-treated with hydrogen peroxide (H_2O_2) to remove organic material (Walling *et al*., 1999b; Sugita and Marumo, 2001; Collins *et al*., 2010a; 2010b). To encourage the decomposition of organic matter, concentrated hydrogen peroxide and distilled water (2:1 ratio) was added to the samples and gently heated at 70 °C for approximately 1 hour until a clear supernatant was evident above the sample (Mikutta *et al*., 2005). After the beaker was cooled to room temperature, the contents were transferred to a centrifuge tube and centrifuged at 3000 rpm using an MSE Harrier 15/80 centrifuge machine, until a clear supernatant was visible. This was subsequently discarded. A chemical dispersant (sodium hexametaphosphate solution) was then added to each sample to aid disaggregation; these were then agitated using a manual whirlmixer and immersed in an ultrasonic bath to aid particle disaggregation. Once the samples were adequately disaggregated for the analysis, they were centrifuged again to form a ‘slurry’ solution and then added individually to a Hydro 2000MU dispersion unit on the Malvern Laser Granulometer (Figure 3.18). Between 10 and 20% of each sample was added to 800 ml of water in this dispersion unit, which contained a pump, stirrer and sonication probe to aid dispersion and to ensure bias-free sampling (Storti and Balsamo 2010). The samples were subjected to constant high speed automated mixing (at 2500 rpm) and ultrasonic dispersion for 60 seconds prior to their delivery to the Malvern analysis chamber (Sperazza *et al.,* 2004).

Figure 3.18 The Malvern Laser Granulometer and Hydro 2000MU dispersion unit*.*

The dispersion unit and internal sample cell was thoroughly flushed out with clean water after each sample was analysed to suppress the effects of inter-sample contamination. Each sample output was displayed in the form of particle size distribution frequency graph reports and provided an estimate of the SSA. Particle size analysis on the specific sand, silt and clay content was conducted on just the suspended sediment samples to identify any spatial and temporal grain size variations within each sub-catchment. These grain size distributions were also added to the larger grain size data (obtained from the initial sieving) to give a full suite of grain-size distribution categories for each sink sample.

3.4.2 Geochemical Property Analysis

According to Walling *et al*. (1993), the complex physico-chemical sorting of eroded material renders sediment tracing based on single parameters unreliable at discriminating sources of fine sediment. Therefore, in order to identify sources of fine sediment in the Lugg catchment a sediment source tracing drew on composite fingerprinting (Walling, 2005). A total of 20 potential diagnostic geochemical properties, incorporating a range of alkali and alkaline earth, basic, semi and transition metals were selected for analysis of suspended sediment source samples and potential source material (Table 3.9).

Table 3.9 Diagnostic geochemical properties (20) included in the analytical programme.

Alkali and Alkaline Earth Metals	Basic Metals	Semi-Metals	Transition Metals
Na, Mg, K, Ca, Sr, Ba	Al, Pb	As	V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Mo, Ag, Cd

The array of geochemical properties analysed were selected to incorporate a wide range of determinants that are influenced by different environmental controls, thus reflecting a considerable degree of independence to facilitate the effective source discrimination of suspended sediments (Walling *et al*., 1999b; Collins and Walling 2002). The properties included in the analytical programme were also selected owing to their successful application in previous studies to discriminate sources of fine sediment (Collins *et al*., 1997c; Owens *et al.,* 1999; Russell *et al*., 2001; Collins and Walling, 2002; Chapman *et al*., 2005; Walling *et al*., 2008). Although more recent studies have used a wider range of elemental properties during analysis (Collins and Walling 2007a; Collins *et al.,* 2010b; 2010c; 2012), the availability of analytical equipment and experience at the University of Portsmouth rendered the selection of geochemical properties the most appropriate for this study.

The inability to provide a globally-applicable tracer technique to discriminate sediment sources in all catchments (Davis and Fox, 2009) has led to a number of different tracer properties being adopted. For example, many previous studies have identified the provenance of suspended sediment by utilising the mineral magnetic properties of potential source materials (Caitcheon 1993; Slattery *et al.,* 1995; Walden *et al*., 1997; Foster *et al*., 1998; Lees, 1999). However, mineral magnetic property analysis was not considered appropriate in this study as the use of this technique frequently introduces several potential problems, which could have a negative influence on the effectiveness of fingerprinting certain suspended sediment samples (Walden *et al.,* 1997). For instance, the elevated variability of mineral magnetic properties for specific catchment sediment sources can hamper the discrimination of individual sources (Collins and Walling, 2002). Furthermore, only a small number of source types can realistically be used when modelling sediment provenance based on mineral magnetic properties, which can severely restrict the successful modelling (Lees, 1994). Owing to the lack of dimensionality and non-linear additive nature of mineral magnetic properties, the data sets can also be difficult to employ in the current generation of sediment mixing models (Dearing, 2000).

Similarly, radionuclide analysis has also been used in various suspended sediment fingerprinting studies (Peart and Walling, 1986; He and Owens, 1995; Walling and Woodward, 1995; Zhang and Zhang, 1995; Wallbrink *et al*., 1996; 1998; Collins and Walling, 2007b). Radionuclide property concentrations are independent of soil type and underlying geology and are therefore compatible to use in homogeneous catchments, which dramatically increases its validity in fingerprinting studies (Walling 2005). However, although the use of such fingerprint properties has been valuable in distinguishing between surface and sub-surface sediment sources (Walling and Woodward, 1992; Kronvang *et al.,* 1997; Caitcheon *et al.,* 2001; Walling 2004), there is uncertainty surrounding the temporal representativeness of spatially diverse sediment sources (Owens *et al*., 1999). Consequently, radionuclide properties were excluded from this study.

Compared with other tracer techniques, a simple relationship exists between particle size and geochemical tracer properties (Motha *et al.,* 2002). A particle size correction factor can consequently be produced enabling the accurate determination of suspended sediment sources. Geochemical fingerprint properties were therefore considered to be the most appropriate tracers to identify the provenance of suspended sediments within the Lugg catchment.

The geochemical element concentrations of the suspended sediment and potential source samples were analysed using Inductively-Coupled Plasma Mass Spectrometry (ICP-MS) following sample preparation by acid (aqua regia) extraction (Allen, 1989). Organic matter was not removed prior to this pre-treatment (Collins *et al*., 2010a) since the removal of organic matter, particularly through use of hydrogen peroxide, has been shown to alter the chemical composition of elemental properties (Mikutta *et al.,* 2005; Wagai *et al.,* 2009). A representative 2-3 g of the <1 mm fraction of all suspended sediment and potential source samples were crushed to a fine powder using a pestle and mortar and were subsequently weighed to 0.5000g (± 0.005g) using a four decimal-place balance. A 20 ml 3:1 mixture of nitric acid (HNO_3) and hydrochloric acid (HCl) was used to produce aqua regia (Sastre *et al.,* 2002; Melaku *et al.,* 2005), which was slowly added to each sample and refluxed on a hotplate under a fume hood for 1 hour. Care was taken throughout the reflux to avoid the sample drying out, adding small amounts of distilled water. Once the extraction had ceased, the samples were filtered through ashless Whatman grade 452 (2.7 µm) filter papers into 50 ml volumetric flasks. Distilled water was added to the volumetric flasks, which were then decanted into 15 ml sample tubes ready for elemental analysis (Figure 3.19).

The aqua regia extraction process is widely used to determine trace element values in soils and sediments (Taraškevičius *et al.,* 2013). However, Chen and Ma (2001) established that this method was less accurate in determining the elemental concentrations in soils compared to other techniques, for example microwave acid digestion. Nevertheless, a subsequent study conducted by Sastre *et al.* (2002) found that for samples with low organic matter content (< 70%) such as agricultural topsoils, the aqua regia extraction method was suitable for the estimation of elemental properties. Although this particular technique does not dissolve the silicate material within the samples, Rodríguez Martín *et al.,* (2006) confirmed that residual silicates in topsoil samples do not display high metal concentrations and, therefore, the resulting values can be considered representative of the total metal concentration.

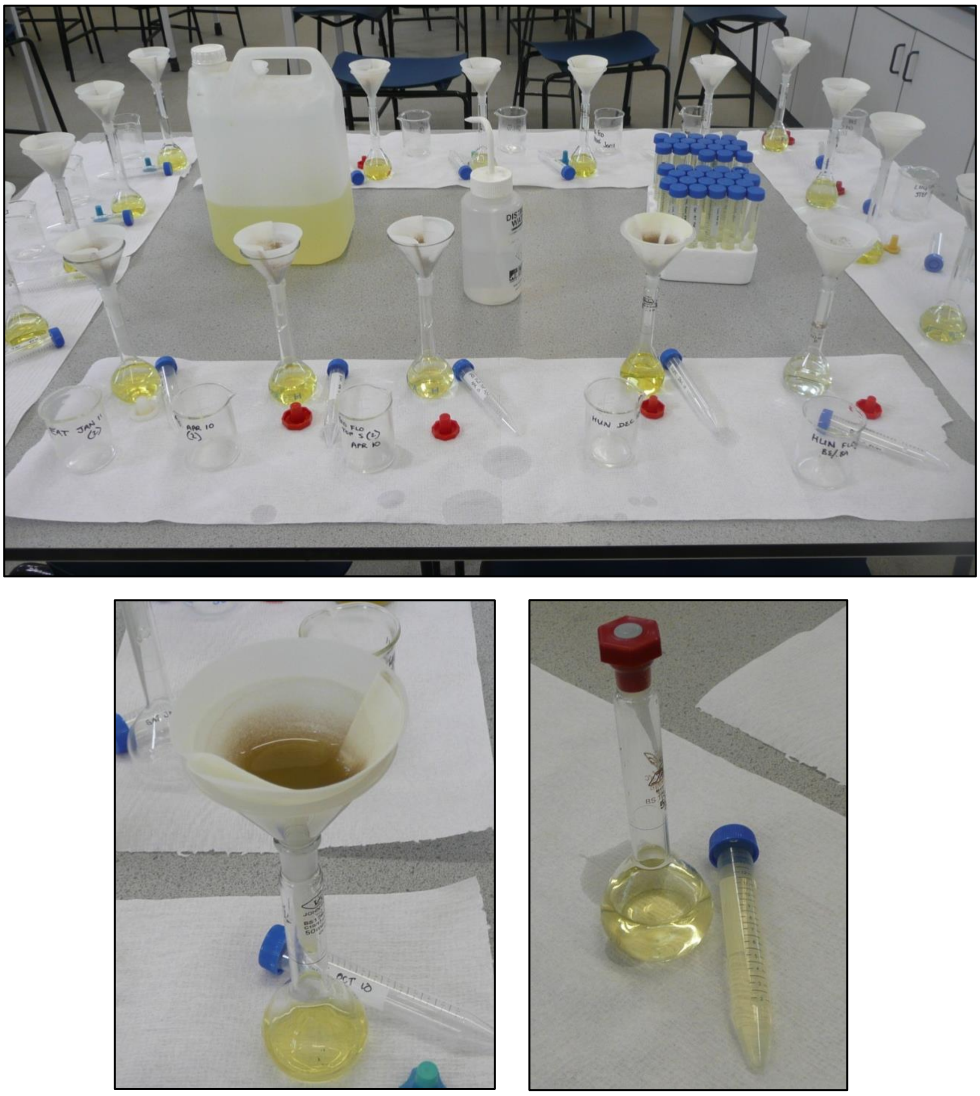


Figure 3.19 The acid extraction pre-treatment method.

For quality control purposes, a Certified Reference Material (CRM) was analysed with each batch of 20 samples to ensure that the extraction process was reliable and accurate (Namieśnik and Zygmunt 1999). The CRM used (Montana 2710) has been found to be one the most useful reference material for metal concentrations in soil samples (Van Herreweghe *et al*., 2003; Jochum and Brueckner, 2008). A number of replicate samples were also analysed throughout this process to ensure the outputs from the ICP-MS yielded accurate and reliable data. In addition, it was important to compensate against the background signature of the aqua regia mixture used throughout the digestion method. By analysing reagent analytical blank samples during the process, the concentrations derived during the ICP-MS analysis were subsequently corrected. Many replicate samples were also analysed during this process to evaluate the reproducibility of the data.

An Agilent 7500ce ICP-MS at the University of Portsmouth (Figure 3.20) was used to determine the concentration of individual elemental properties within the suspended sediment and potential source samples. It offered rapid analysis capabilities at low detection limits (ppt) and high spectral resolution for multi-element detection (Eggins *et al.,* 1997; Ammann, 2007). The instrument was configured in the collision mode for the reliable removal of all matrix interferences with a 25 ppb Rh internal standard and the resulting calibrations were constructed from multiple-element internal standard solutions. Accuracy and precision are estimated to be better than ± 5% relative standard deviation based on replicate sample analyses and CRM analytical results.

Figure 3.20 The Agilent 7500ce ICP-MS.

During its operation, the samples were introduced into the ICP-MS by an integrated sample introduction system (ISIS) consisting of a pump and a nebulizer, where the sample was converted to a fine aerosol in a spray chamber (Brouwers *et al*., 2008). The droplets were directed into the sample injector of a plasma torch, where they underwent a number of physical changes. The vapour was atomised in the plasma at 6,000-8,000 K before eventually becoming ionised. The resulting positively charged ions where then efficiently and consistently transported through an interface from the plasma to the ion optic system of the mass spectrometer. Particulates, neutral species and photons, which can cause signal instability affecting the precision and accuracy of the instrument, were consequently prevented from reaching the mass spectrometer and detection system (Thomas, 2001). The mass separation device utilised quadrupole mass filter technology to separate the ions based on their mass-tocharge (*m/z*) ratios, enabling the selected ions to be transmitted to the detector and measured. Figure 3.21 shows a schematic diagram of the ICP-MS process. The output signals were converted into individual elemental concentrations (ppm) that were subsequently corrected for sample specific solution volume and sediment weight. The results were then transferred to an excel spreadsheet, detailing individual element concentrations for each suspended sediment and potential source sample collected.

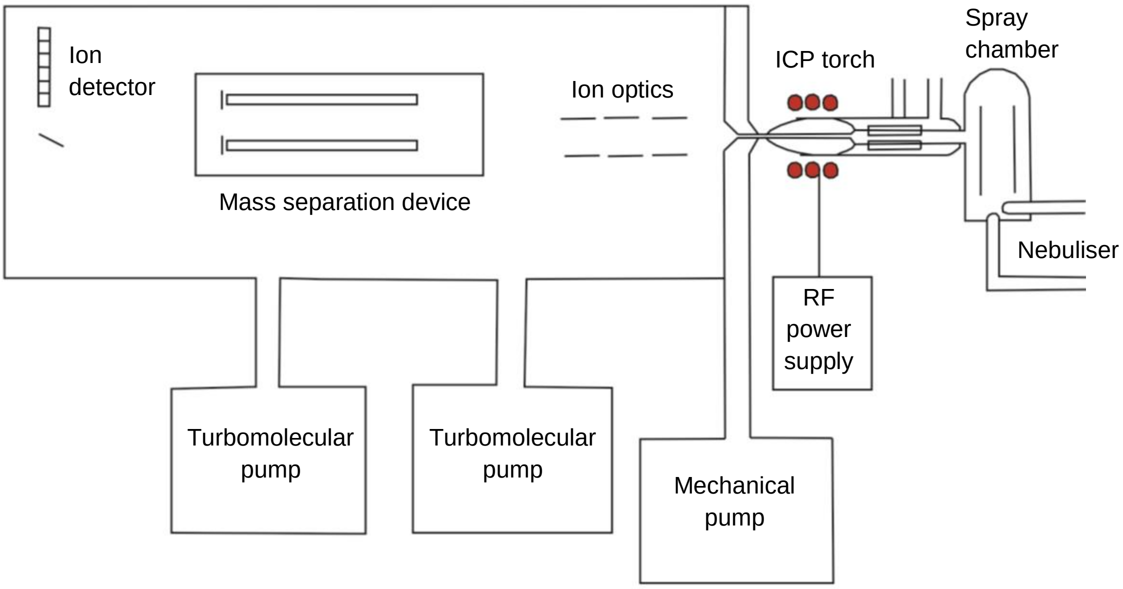


Figure 3.21 Schematic diagram of the ICP-MS process (based on Thomas, 2001).

3.5 Summary

This chapter has detailed the field and laboratory methods adopted throughout this study to determine the patterns and provenance of fine sediment within the Lugg catchment. The criteria and approach developed for selecting suitable monitoring sites has been outlined, along with the monitoring strategy implemented and the field equipment drawn upon. The procedure used for the representative collection of potential source material and the technique adopted for the collection of suspended sediment samples has also been described. Furthermore, the laboratory procedures applied during the sample preparation and subsequent analysis have been outlined. The statistical analysis of composite fingerprint data for source apportionment is detailed in Chapter 5.

CHAPTER 4

SPATIO-TEMPORAL VARIATIONS IN SUSPENDED SEDIMENT

4.1 Introduction

This chapter presents the results and interpretation from the continuous sediment and flow monitoring strategy developed at the five study sites within the Lugg catchment (see Chapter 3, section 3.2.2). Despite the need for reliable information of suspended sediment fluxes, (see Chapter 1), such data records are frequently short-lived or lacking (Collins *et al.,* 2017c). As such, the fine sediment problem in the Lugg catchment is founded on a limited database which involves the collection of 12 spot samples of suspended sediment loadings per annum. The large variation and low frequency of sampling of suspended sediment concentration represented by this dataset results in uncertain estimates of the annual average concentration (Anthony and Collins, 2006). Therefore, the aim of the suspended sediment monitoring strategy was to provide a high quality continuous record of suspended sediment to better understand the fine sediment problem in the catchment and to assess the spatio-temporal variations in suspended sediment delivered to key salmonid spawning sites.

The objectives of this chapter are to (i) establish the quantity and character of fine sediment in the Lugg catchment by providing an assessment of siltation at key monitoring sites through quantifying the grain-size characteristics of the substrate material and identifying the particle size composition of suspended sediment; (ii) assess the suspended sediment response and variation in suspended sediment characteristics at each site; and (iii) evaluate the suspended sediment dynamics and identify patterns of fine sediment supply during different temporal storm events.

4.2 Rainfall and Flow Characteristics

Figures 4.1 and 4.2 show the rainfall and discharge characteristics at each monitoring site over the period of study. The river regime at all sites is characterised by periods of low flow interspersed with high discharges of flashy nature. This flashy nature is particularly evident at the Hunton monitoring site following a period of heavy rainfall (Figure 4.1). High flow events occurred throughout the monitoring period and mostly occurred during the winter months. However, high flow events also occurred during heavy summer rainfall events. The most extreme event during the monitoring period at the Hunton monitoring site occurred in October 2010 when discharge peaked at 24 m^3 s^{-1} following a period of heavy rainfall in excess of 15mm per day (Figure 4.1). The effect of this event was also noticeable in the flow records for the other monitoring sites (e.g. 30 m^3 s^{-1} at the Broadward monitoring site), but peaks in discharge were delayed and transpired for longer. This highlights the flashy nature of the river regime in response to heavy rainfall events in the upper parts of the catchment. Another significant flow peak occurred in April-May 2012 following a sustained period of heavy rainfall. This period represented the most extreme event at the Broadward monitoring site where discharge peaked at 32 m^3 s^{-1} (Figure 4.1).

The most extreme event during the monitoring period at the Eaton monitoring site occurred in July 2012 when discharge peaked at 46 m^3 s^{-1} following a two-day period where rainfall totalled over 38 mm (Figure 4.2). The effect of this was also evident in the flow records for the other monitoring sites in the lower parts of the catchment. For example, discharge peaked at 34 m^3 s^{-1} and 39 m^3 s^{-1} at the Marlbrook and Lugwardine monitoring sites respectively during this event. Other significant flow peaks occurred during the period November 2009 – January 2010 which coincided with frequent rainfall events (12% of the total rainfall accumulated during the whole monitoring period occurred during this period). This period represented the most extreme event at the Marlbrook monitoring site where discharge peaked at 47 m^3 s^{-1} in January 2010 (Figure 4.2).

The majority of flows over the monitoring period at the Hunton and Broadward sites are below 5 m^3 s^{-1}, with flows greater than 10 m^3 s^{-1} occurring for 6 and 14% of the time respectively. In contrast, the majority of flows at the monitoring sites in the lower parts of the catchment are above 5 m^3 s^{-1}, with flows greater than 10 m^3 s^{-1} occurring for 22% of the time at the Marlbrook monitoring site. Flows greater than 20 m^3 s^{-1} occur for approximately 10% of the time at the Lugwardine monitoring site, whereas flows of this magnitude occur for less than

1% of the time at the Hunton monitoring site. Mean flows are higher in the winter (October – March) than in the summer (April – September). However, as noted above, the summer is characterised by some extreme flow events coinciding with heavy rainfall events. This suggest that suspended sediment transport in the Lugg catchment is likely to be episodic.

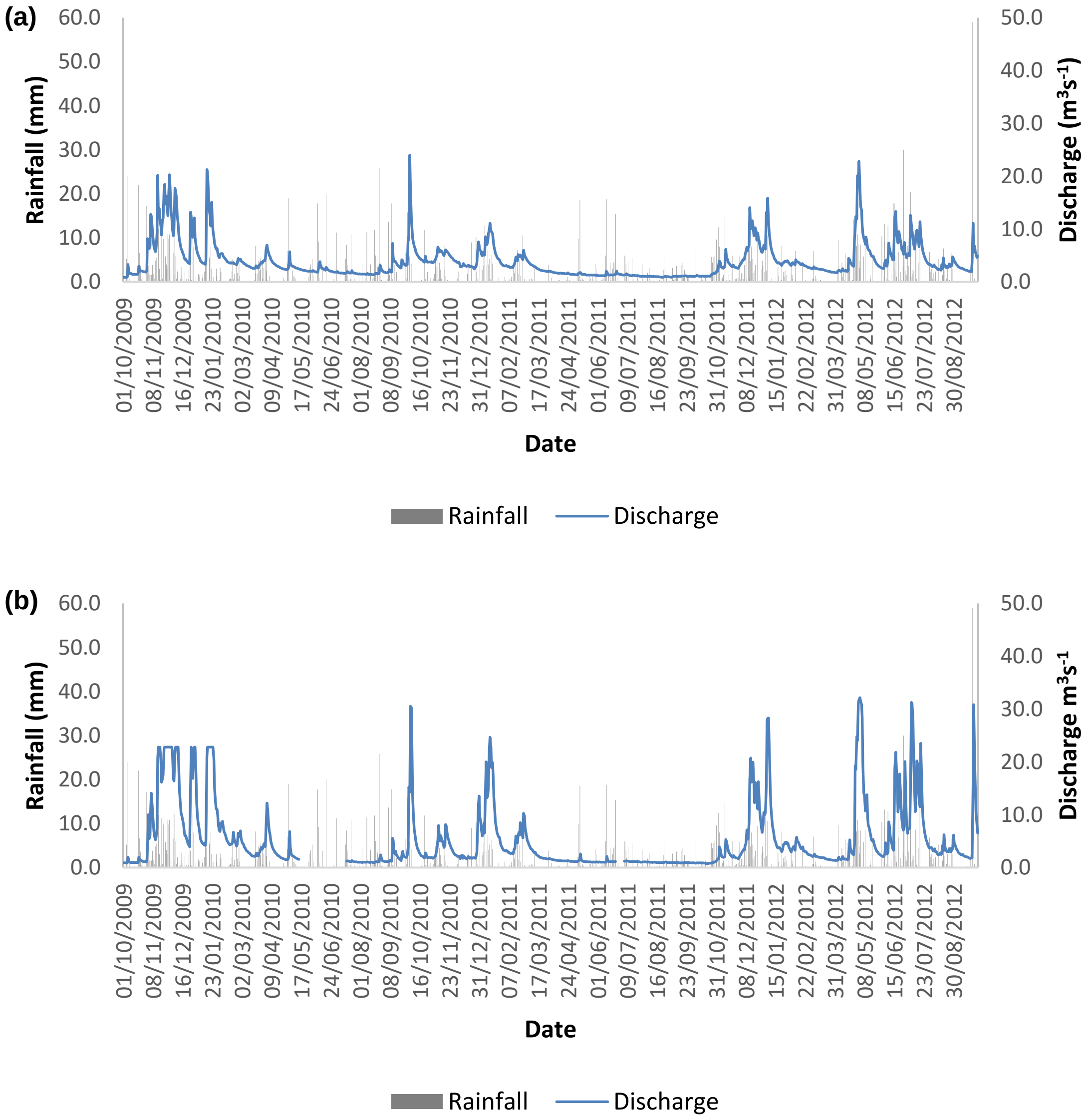


Figure 4.1 Daily rainfall and flow records for the (a) Hunton and (b) Broadward monitoring sites on the River Arrow *(rainfall data extracted from the Shobdon Airfield gauging station, Met Office 2013).*

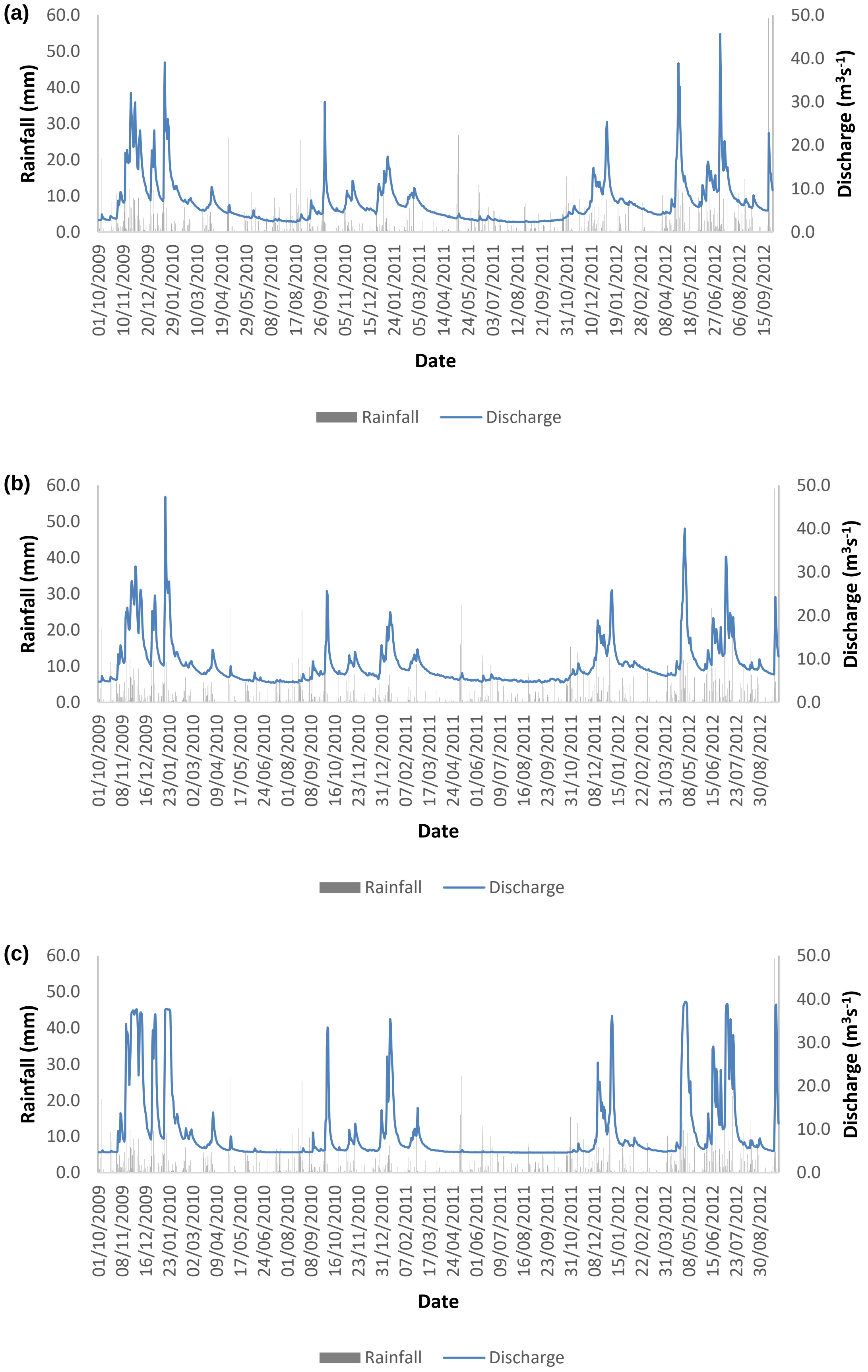


Figure 4.2 Daily rainfall and flow records for the (a) Eaton, (b) Marlbrook and (c) Lugwardine monitoring sites on the River Lugg *(rainfall data extracted from the Leominster gauging station, Environment Agency 2013).*

4.3 Fine Sediment Characteristics

4.3.1 Site-based grain-size characteristics

Owing to the important biological implications of the fraction of fine sediment in the subsurface material of a gravel-bedded river (Cui *et al.,* 2008), it was necessary to assess the gravel quality at each monitoring site. Information concerning the grain-size characteristics and the concentration of fine sediment (< 2 mm) within the gravel substrate voids was provided using Wolman's (1954) sampling protocol and a freeze-coring technique (see Chapter 3). The summary statistics for the freeze core data are provided in Table 4.1. Core size is dependent on a range of factors, including sediment composition and freezing efficiency, which are controlled by flow velocity and water temperature. However, the core statistics are comparable to previous studies (Crisp and Carling, 1989; Milan *et al*., 2000; McEwen *et al.,* 2012).

Table 4.1 Summary of freeze-core data for the monitoring sites.

Site	***n***	**Core length (cm)**	**Core width (cm)**	**Core weights (kg)**		
				Upper 0-15 cm	**Lower 15-30 cm**	**Total**
1 Hunton	5	29.0	21.4	15.8	28.8	44.6
2 Broadward	5	32.6	19.2	18.7	27.7	46.4
3 Eaton	5	29.8	27.4	15.0	22.5	37.5
4 Marlbrook	5	35.0	21.6	35.0	33.7	68.7
5 Lugwardine	5	35.8	17.2	17.2	17.1	34.3

The grain-size characteristics for the armour layer and substrate matrix sediments are provided in Table 4.2. The substrate is overlain by a well-developed armour layer at all the sites sampled. On average the d_{50} of the armour layer at each site was 45.6 mm and ranged from a maximum of 61.5 mm at site 4 (Marlbrook) to 30 mm at site 3 (Eaton). This is comparable to typical sandstone streams sampled by Milan *et al*., (2000), who reported an average d_{50} value of 38 mm, ranging between 13 and 60 mm. Although the armour layer at site 3 (Eaton) is comprised of fine material, the d_{max} is coarser (270 mm) in comparison with the other sites, which range between 140 and 157 mm. This indicates that the armour layer is mainly comprised of fine material interspersed with coarser clasts.

Table 4.2 Grain-size summary characteristics at each monitoring site.

Site	Armour Layer (mm)		Substrate matrix <2mm (% by weight)		
	d_{50}	d_{max}	Whole core	Upper core	Lower core
1 Hunton	47.0	140.0	15.8	18.4	14.4
2 Broadward	47.0	154.0	38.7	42.2	36.3
3 Eaton	30.0	270.0	33.7	32.8	34.8
4 Marlbrook	61.5	157.0	26.3	21.0	31.8
5 Lugwardine	42.5	142.0	70.6	58.4	82.6
Average	*45.6*	*172.6*	*37.0*	*34.6*	*40.0*

The < 2mm substrate matrix concentrations on average were 37% (by dry weight). The lowest concentrations of matrix material are found at site 1 (Hunton) and site 4 (Marlbrook) with 15.8 and 26.3% respectively, whereas the highest concentration is found in the lower reaches River Lugg (site 5 Lugwardine) with 70.6%. Average concentrations of substrate matrix are 34.6 and 40% for the upper 0-15 cm and lower 15-30 cm respectively (Table 4.2). Data on upper and lower core sections indicate that the near-surface layer contains less fine sediment than the lower layer at the three sites on the River Lugg, although this is marginal at site 3 (Eaton). This is most evident at site 5 (Lugwardine) where the lower core section has 82.6% < 2mm in comparison to 58.4% < 2 mm in the upper core. This is a reflection of higher intra-gravel flows that percolate the near surface substrate, flushing out fine sediment (McEwen *et al.,* 2012). In contrast, the two sites on the River Arrow (site 1 Hunton and site 2 Broadward) contain greater < 2 mm concentrations in the surface 0-15 cm of substrate compared to the lower 15-30 cm.

Figure 4.3 shows the average particle size distribution of the sampled substrate material. It is evident that the siltation of gravels is greatest at site 5 (Lugwardine) with the gravel substrate dominated by < 2 mm material (70.6%). In contrast, it is evident that substrate gravels at site 1 (Hunton), located in the upper Arrow catchment comprise of the lowest percentage of < 2 mm material

(15.8%). In comparison to this site, the gravel substrate is much finer in the lower reaches of the River Arrow with < 2 mm concentrations of 38.7%. Furthermore, it is notable that the substrate at site 4 (Marlbrook) located downstream of the Arrow confluence is coarser than the substrate at the site directly upstream of the confluence (site 3 Eaton) with < 2 mm concentrations of 26.3% compared to 33.7%.

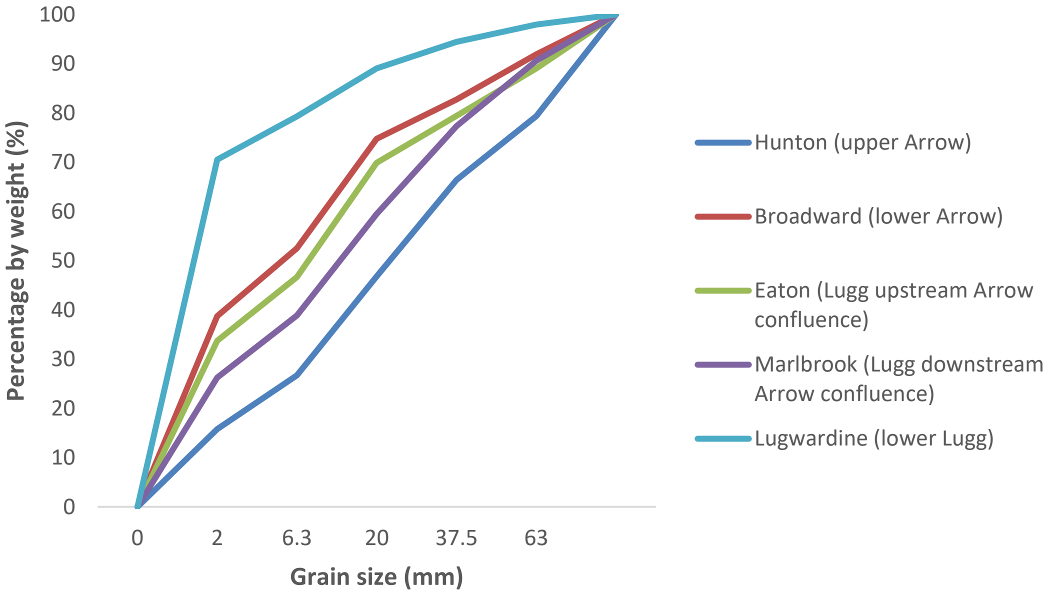


Figure 4.3 Freeze core particle size distribution of the substrate material sampled at each monitoring site.

The sand, silt and clay concentrations of the < 1 mm substrate material at each monitoring site are shown in Table 4.3. It is notable that all sites are dominated by silt, with the greatest concentrations found at site 1 (Hunton). Greatest sand concentrations are found at sites 2 (Broadward) and 5 (Lugwardine), with concentrations of 34 and 31% respectively. Whilst clay concentrations are low at all sites, it is evident that the three River Lugg sites have higher concentrations in comparison with the River Arrow sites, with concentrations between 6.6 and 7%. Some marginal vertical variability is also evident in the distribution of sand, silt and clay (Table 4.3). Greater sand concentrations are shown in the lower 15-30 cm of substrate at each site, with the exception of site 1 (Hunton), where greater concentrations are found in the surface 0-15 cm. This pattern is reversed when considering silt concentrations, although the differences are marginal. The upper core sections are found to have slightly higher concentrations of clay at sites 2 (Broadward), 3 (Eaton) and 5 (Lugwardine), whereas at sites 1 (Hunton) and 4 (Marlbrook) greater concentrations of clay are found in the lower 15-30 cm of substrate.

Table 4.3 Percentages of sand, silt and clay for the monitoring sites in the < 1 mm fraction (upper: lower core ratios are indicated in brackets).

Site	Sand	Silt	Clay
1 Hunton	24.0 (1.25)	70.3 (0.94)	5.7 (0.87)
2 Broadward	34.0 (0.92)	60.1 (1.04)	5.9 (1.05)
3 Eaton	28.0 (0.91)	65.0 (1.03)	7.0 (1.07)
4 Marlbrook	29.6 (0.90)	63.4 (1.06)	7.0 (0.90)
5 Lugwardine	31.0 (0.75)	62.4 (1.15)	6.6 (1.05)

4.3.2 Particle Size Composition of Suspended Sediment

Suspended sediment was continuously collected over the monitoring period at each field site using time-integrated sediment samplers (see Chapter 3, section 3.2.3). Table 4.4 presents information on the mean particle size characteristics for all sampling sites between 2009 and 2012. In general, there is considerable variation in the particle size characteristics between sites. The average d_{50} values range from 13.8 µm at site 5 (Lugwardine) to 23.6 µm at site 1 (Hunton). In all cases, more than 95% of the suspended sediment is < 63 µm, ranging between 97.2% at site 3 (Eaton) and 98.6% at site 5 (Lugwardine). The < 2 µm fraction accounts for between 7.9% (site 1 Hunton) and 12.5% (site 5 Lugwardine) of the suspended sediment. Therefore, it is evident that the suspended sediment transported through the catchment is finest at site 5 (Lugwardine) and coarsest at site 1 (Hunton). Furthermore, the quantity of suspended sediment sampled at each site varies, with sediment fluxes ranging from 0.7 to 1.7 g d^{-1} at sites 3 (Eaton) and 5 (Lugwardine respectively (Table 4.4).

Table 4.4 Mean particle size and characteristics of suspended sediment collected from each monitoring site.

Site	***n***	**Weight (g d^{-1}) ***	***d_{50}* (µm)**	**% > 63 (µm)**	**% < 63 (µm)**	**% < 2 (µm)**
1 Hunton	22	1.0	23.6	2.7	97.3	7.9
2 Broadward	19	1.3	15.0	2.0	98.0	10.8
3 Eaton	20	0.7	18.5	2.8	97.2	12.1
4 Marlbrook	19	1.3	16.9	1.6	98.4	10.9
5 Lugwardine	18	1.7	13.8	1.4	98.6	12.5

** sample weight (g d^{-1}) calculated as total weight divided by the total number of days the time integrated sampler was installed in the channel.*

Figure 4.4 better illustrates the contrasting average d_{50} values at each monitoring site. The two sites located in the lower parts of the Arrow and Lugg catchments (Site 2 Broadward and site 5 Lugwardine) have finer d_{50} values. It is evident that the suspended sediment gets progressively finer at sites located further down the catchment. This is evident for both the River Arrow and River Lugg. The effect of the Arrow tributary is also notable with variable d_{50} values upstream (site 3 Eaton) and downstream (Site 4 Marlbrook) of this confluence. The relatively short distance between these two sites and the lack of large tributaries converging with the main channel suggests that fine sediment from the Arrow catchment is transported through the whole Lugg system.

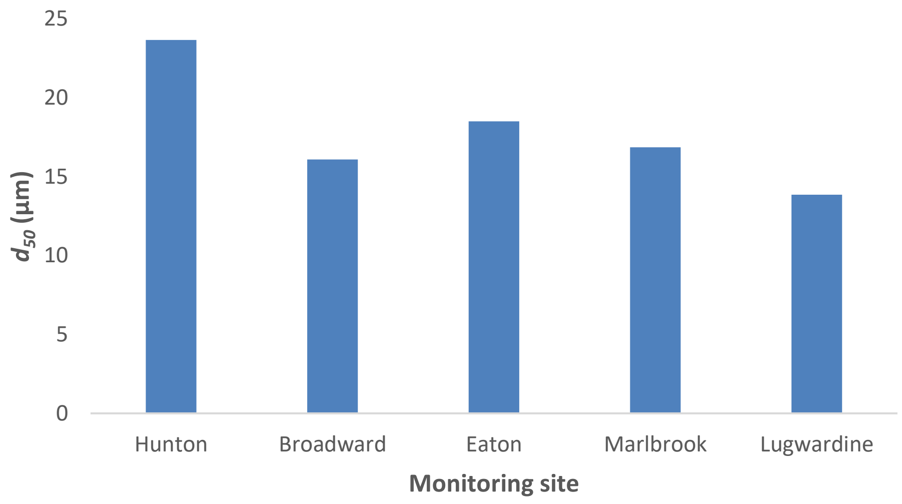


Figure 4.4 Average d_{50} values for the suspended sediment collected at each monitoring site.

In addition to spatial variations, there is also considerable temporal variation in particle size characteristics of the suspended sediment collected during different flow events at the monitoring sites. Appendix 1 (1.1-1.5) present summary characteristics of suspended sediment collected within the time integrated sediment samplers at each site. The d_{50} values at site 1 (Hunton) range from 16.2 µm during the October – December 2010 sampling period to 46.8 µm during the August – September 2011 sampling period (Appendix 1.1). In all cases, more than 90% of the suspended sediment is < 63 µm, ranging between 92.8% (August – September 2011) and 100% (February – March 2012). It is notable that the suspended sediment collected at this site is generally finer during the winter months in comparison to the summer (Figure 4.5). For example, the d_{50} values range between 16.3 to 46.8 µm during the summer season, whereas the corresponding d_{50} values in the winter range between 16.2 and 26.3 µm (Appendix 1.1). The average amount of suspended sediment collected in the time integrated samplers is also greatest during the winter period. The coarsest d_{50} values generally coincide with sampling periods with the least amount of sediment being transported. This is especially evident for sampling periods ranging between March and November 2011 where the percentage of < 63µm material is at its lowest.

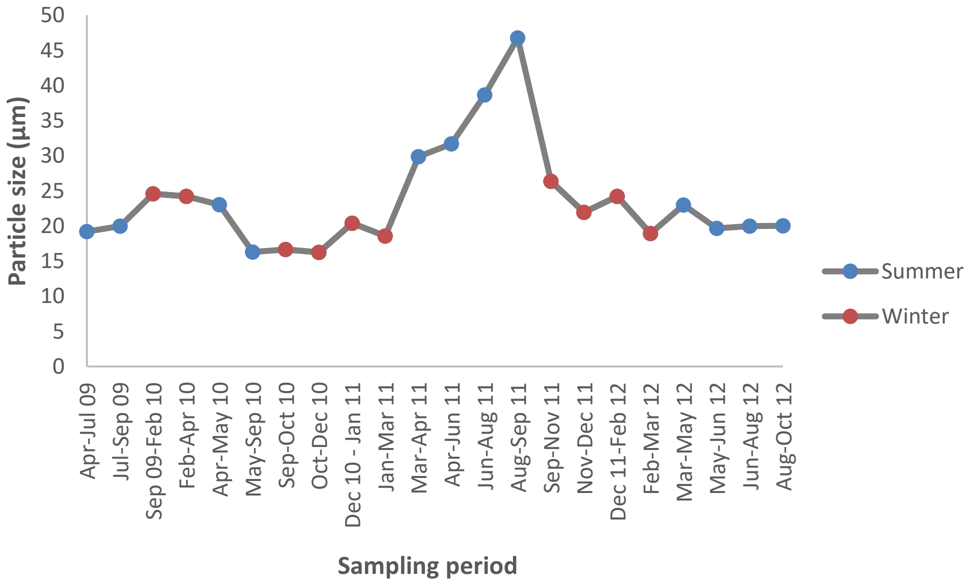


Figure 4.5 Temporal variation in the d_{50} values of suspended sediment collected at site 1 (Hunton).

In contrast, the d_{50} values of the suspended sediment collected at the downstream section of the River Arrow (site 2 Broadward) are much less variable, with a minimum value of 11.1 µm during the April – June 2011 sampling period and a maximum of 21.2 µm, during the December 2010 – January 2011 sampling period (Appendix 1.2). In all cases, more than 95% of the suspended sediment is < 63 µm, ranging between 96.8 and 99.1% for the February – March 2012 and March – May 2010 sampling periods respectively. The < 2 µm fraction accounts for between 8.1% (September – November 2011) and 13.6% (April – June 2011). The average amount of sediment collected in the time integrated samplers is greater in the winter period, although the large amount during the December 2010 – January 2011 sampling period is likely to drive this. However, unlike the suspended sediment samples collected at the upper section of the River Arrow (site 1 Hunton), the finest d_{50} values and greatest < 2 µm concentrations at this site are associated with the summer months (Figure 4.6).

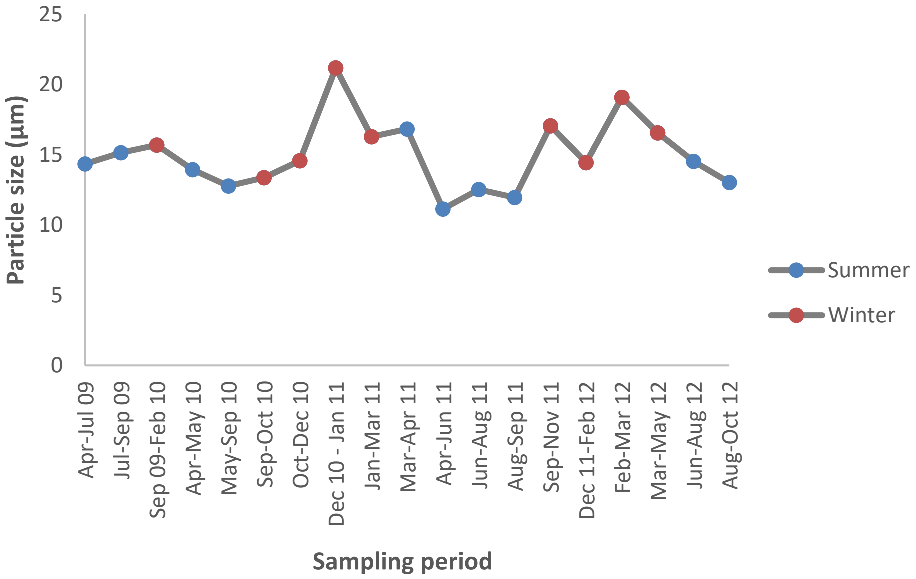


Figure 4.6 Temporal variation in the d_{50} values of suspended sediment collected at site 2 (Broadward).

There are also considerable variations in the grain-size of the suspended sediment collected during different flow events at site 3 (Eaton). For example, the d_{50} values range from 8.6 and 41.4 µm during the April – June 2011 and August – September 2011 sampling periods respectively (Appendix 1.3). More than 90% of the suspended sediment is < 63 µm, ranging between 91.5% (June – August 2011) and 99.1% (March – May 2010 and August – October 2012). Similar to site 1 (Hunton), the suspended sediment collected at this site is generally coarser during the summer months in comparison to the winter, with the notable exception of the April – June 2011 sampling period which is associated with the finest d_{50} value (Figure 4.7). However, there is not a substantial seasonal variation in the average quantity of suspended sediment collected at this site.

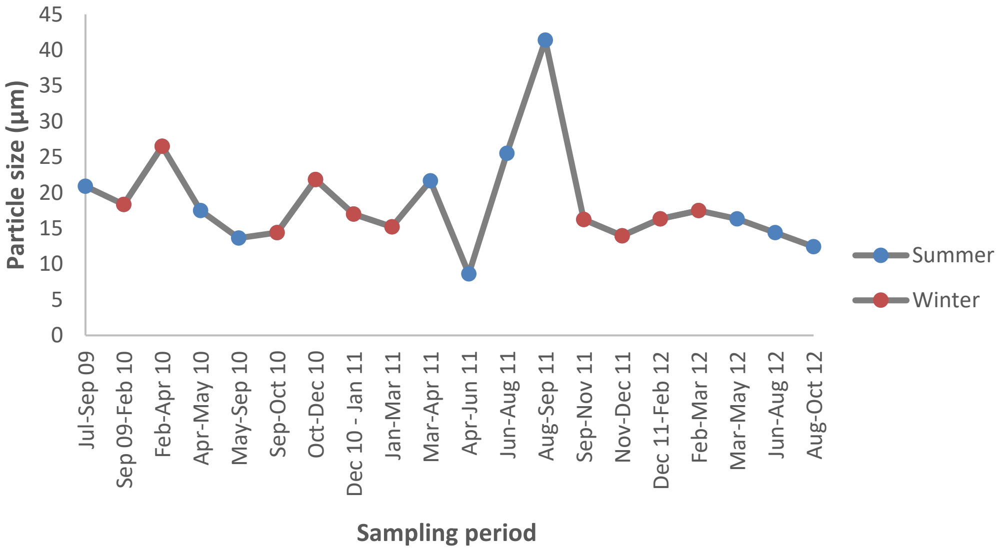


Figure 4.7 Temporal variation in the d_{50} values of suspended sediment collected at site 3 (Eaton).

Furthermore, it is also evident that there are significant temporal variations in the suspended sediment characteristics at site 4 (Marlbrook). The range of d_{50} values are similar to those reported at site 3 (Eaton), with the greatest value associated with the February – March 2012 sampling period (49.7 µm). The finest suspended sediment is associated with the April – June 2011 sampling period, with a d_{50} value of 7.2 µm and a < 2 µm concentration of 20.1% (Appendix 1.4). In all cases, more than 95% of the suspended sediment is < 63 µm, ranging between 96.4% (February – March 2010) and 100% (February – March 2012). The average amount of sediment collected in the time integrated samplers is greater in the winter period with an average sediment flux of 1.6 g d^{-1}. In contrast to the site directly upstream of the Arrow confluence, the finest d_{50}

values at this site are associated with suspended sediment collected during the summer months (Figure 4.8).

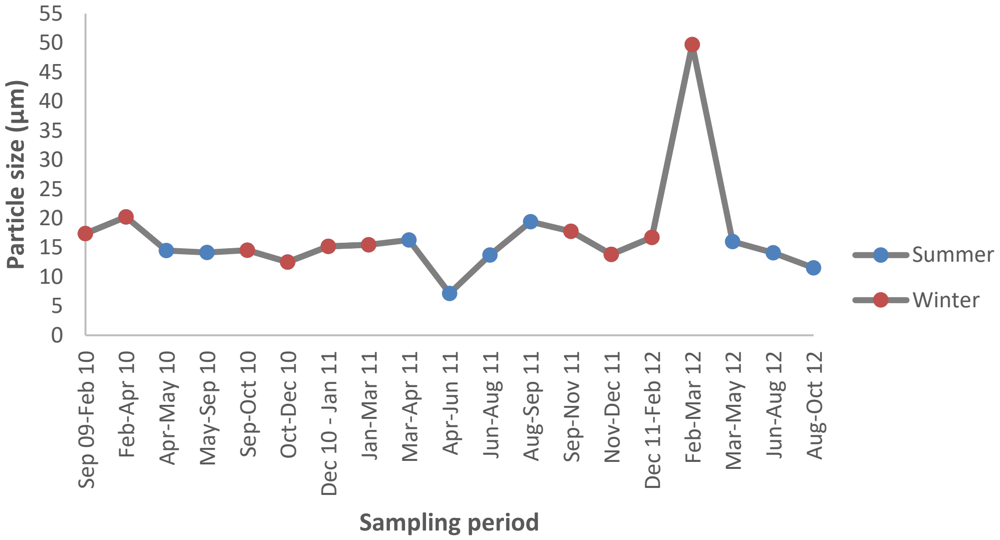


Figure 4.8 Temporal variation in the d_{50} values of suspended sediment collected at site 4 (Marlbrook).

In contrast, there is less temporal variability in the characteristics of suspended sediment collected at the downstream site on the River Lugg site (site 5 Lugwardine). For example, the d_{50} values range from 8.7 µm to 23.8 µm during the May – August 2012 and March – April 2011 sampling periods respectively (Appendix 1.5). In all cases, more than 95% of the suspended sediment is < 63 µm and the < 2 µm fraction accounts for between 7.2% of the sample during March – April 2011) and 17.6% of the sample during May – August 2012. When considering seasonal influences on the suspended sediment at this site, it is evident that in general the d_{50} values are marginally finer during the winter months (Figure 4.9). The average amount of suspended sediment collected in the time integrated samplers is also greatest during the winter period, with an average sediment flux of 2.1 g d^{-1}.

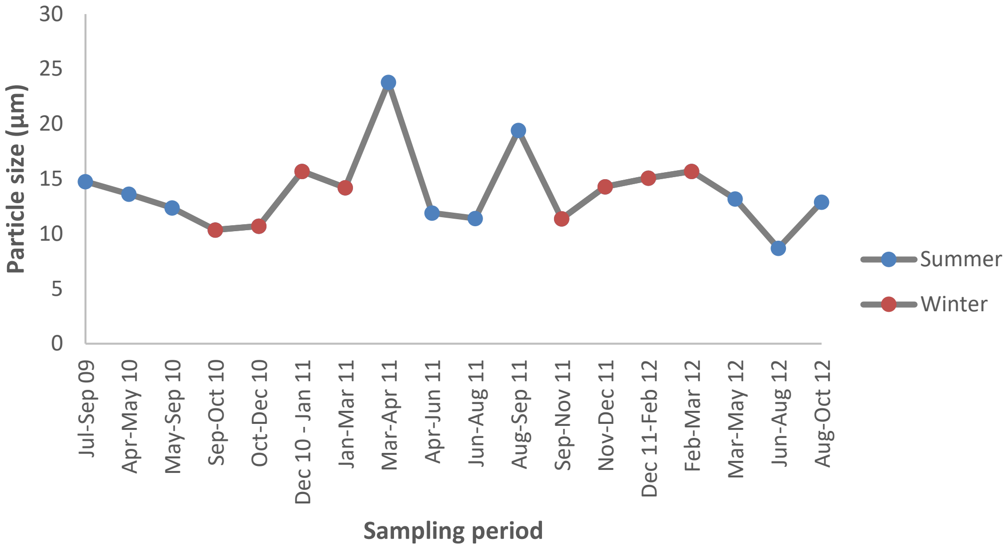


Figure 4.9 Temporal variation in the d_{50} values of suspended sediment collected at site 5 (Lugwardine).

4.3.3 Summary

There are spatial patterns evident in the substrate quality and suspended sediment characteristics at the monitoring sites in the Lugg catchment. It is evident that site 1 (Hunton) located in the upper reaches of the River Arrow has the best quality gravels, with matrix (< 2 mm) concentrations of 15.8%. In contrast, the gravel substrate is finer in the lower reaches of the River Arrow, with < 2 mm concentrations of 38.7% at site 2 (Broadward). The siltation of gravels is greatest at site 5 (Lugwardine), with average < 2 mm matrix concentrations of 70.6%.

Similarly, there is considerable variation in the characteristics of suspended sediment collected over the monitoring period at each site. For example, the suspended sediment characteristics get progressively finer at sites located further down the catchment. This is evident for the sites on both the River Arrow and River Lugg. The effect of the River Arrow on the sediment characteristics transported through the Lugg catchment can be highlighted in Figure 4.4, with a finer d_{50} value associated upstream of this confluence (site 3 Eaton) compared to downstream (site 4 Marlbrook). In all cases, more than 95% of the suspended sediment collected at each site is < 63 µm, with the greatest concentration of this size fraction found at site 5 (Lugwardine). This pattern is also observed in the quantity of suspended sediment collected at each site, with the highest average sediment flux (1.7 g d^{-1}) at site 5 (Lugwardine).

In addition, there is considerable temporal variation in the particle size characteristics of suspended sediment collected during different flow events. It is notable that there are distinct seasonal influences, with finer material transported during the winter months at three of the five sites (Hunton, Eaton and Lugwardine), although this pattern observed at the latter site is marginal. This trend is reversed at site 2 (Broadward) and site 4 (Marlbrook), where finer material is transported during the summer period. However, there is less temporal variability associated with the suspended sediment collected at site 2 (Broadward) and site 5 (Lugwardine). Both sites are located in lowest parts of their respective catchments and the gravel substrate is dominated by fine sediment. Furthermore, the quantity of suspended sediment is generally greater during the winter, except at site 3 (Eaton), where the seasonal variation is marginal. This suggests that variations relate to differences in flood magnitude, which may disrupt the bed surface armour layer, and sediment supply from upstream sources.

4.4 Suspended Sediment Flux Monitoring

The suspended sediment flux at each site was calculated using the continuous turbidity monitoring dataset acquired rather than the sediment weights collected in the time-integrated sediment samplers. Phillips *et al*., (2000) documented that these samplers underestimate suspended sediment load during high flow events owing to the relatively small diameter of the inflow nozzle compared to the cross-sectional area of the channel. Furthermore, the time integrated samplers could reflect a single or a large number of events during the time it was deployed in the channel, so it would be difficult to determine loads for individual events. In contrast, continuous turbidity monitoring can generate accurate sediment flux estimates as well as providing detailed information on storm-period fluctuations (Minella *et al*., 2008). It was therefore recognised that a more accurate suspended sediment flux will be calculated using the continuous turbidity data collected at each monitoring site.

4.4.1 Rating Relationships

The calculation of sediment loads requires both discharge and sediment concentration data (Phillips *et al.,* 1999). Continuous stage data recorded at each site was converted to discharge based on site-specific stage-discharge relationships (Figure 4.10). Previous research has found that relationships between suspended sediment and turbidity are often site-specific (Horowitz, 2003; Minella *et al*., 2008). Therefore, site-specific relationships between suspended sediment and turbidity were also generated for each monitoring site to enable the conversion of turbidity units to suspended sediment concentration and to determine the suspended sediment flux (Figure 4.11). The methodology deployed in this study to generate stage-discharge and suspended sediment-turbidity relationships can be found in Chapter 3 (section 3.2.2).

The relationships in Figure 4.10 represent a mixture of cross-sectional velocity calculations and the ‘float method’ during periods of extreme flow conditions. Although the rating curves are based on a limited set of data, R^2 values range from 0.94 to 0.99 and the flow values at site 1 (Hunton) and site 5 (Lugwardine) are similar to the respective gauging stations at ‘Titley Mill’ and ‘Lugwardine’. The relationships in Figure 4.11 represent individual flood events at each site, with the exception of site 2 (Broadward), which represents a relationship between suspended sediment concentration and turbidity from a number of ‘spot’ water samples taken throughout the period of study. There was difficulty establishing a positive relationship at this site during individual rainfall events owing to site-specific issues. Nevertheless, Figure 4.10 confirms the existence of a close relationship between suspended sediment concentration and turbidity at each site with best levels of fit generated from polynomial, power and linear equations. R^2 values ranged from 0.86 to 0.96, which is comparable to the R^2 values reported by Minella *et al.,* (2008) who established relationships for eight different flow events by fitting polynomial and power equations to the generated datasets.

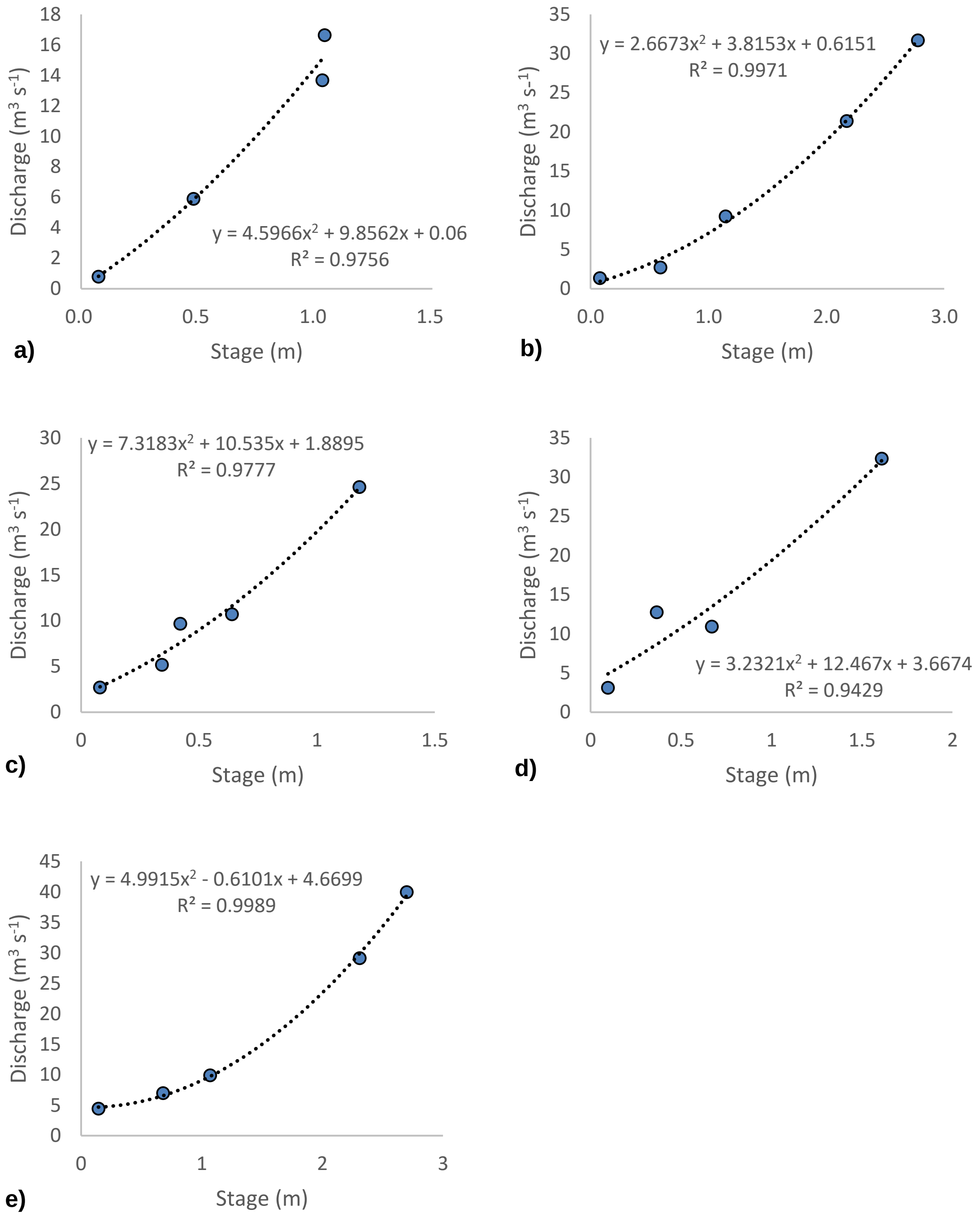


Figure 4.10 Site-specific relationships between discharge and stage a) Hunton, b) Broadward, c) Eaton, d) Marlbrook, e) Lugwardine.

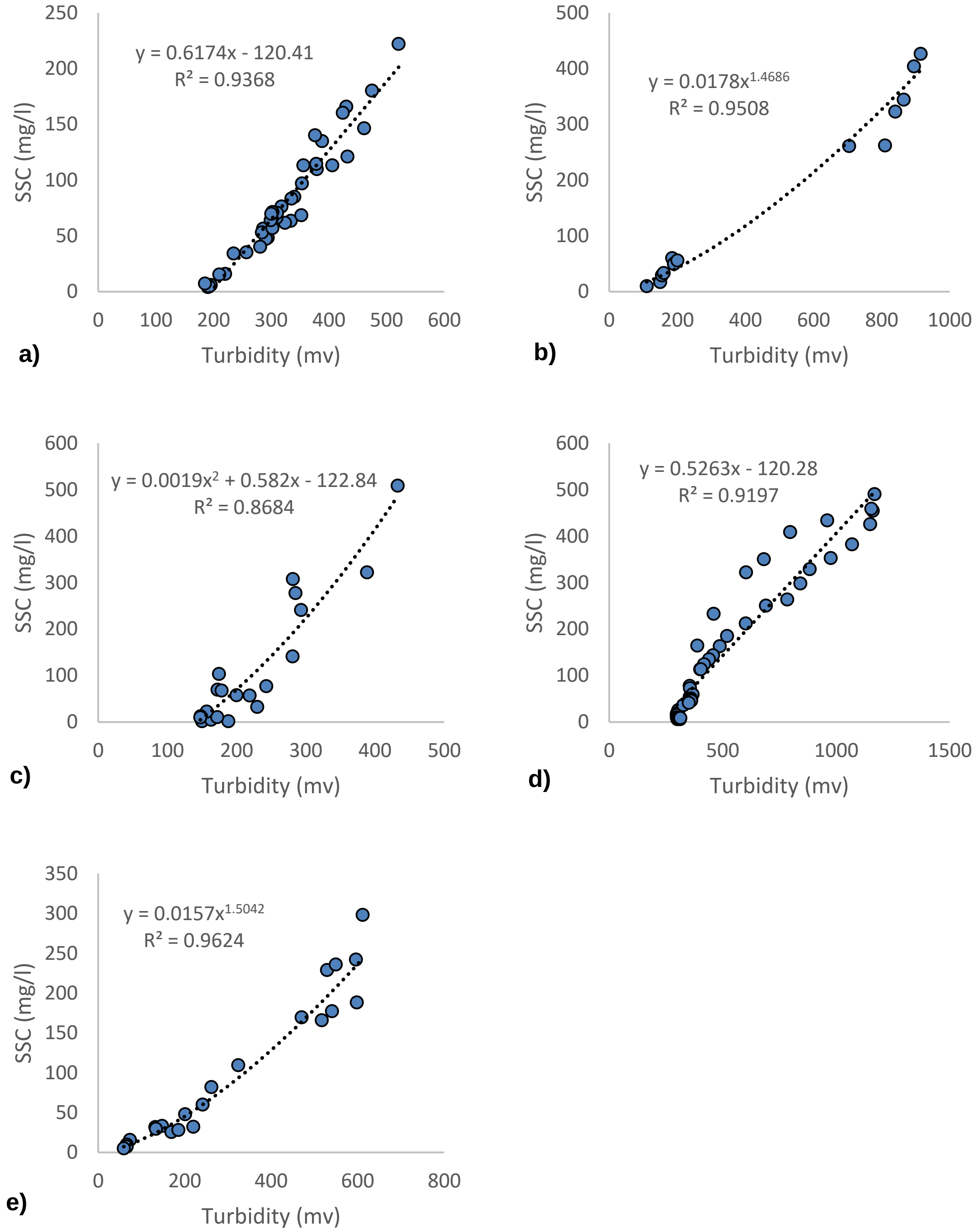


Figure 4.11 Site-specific relationships between suspended sediment concentration (SSC) and turbidity a) Hunton, b) Broadward, c) Eaton, d) Marlbrook, e) Lugwardine.

4.4.2 Suspended Sediment Summary Statistics

Table 4.5 presents summary statistics for the suspended sediment concentration data (mg L^{-1}) recorded at each field site over the entire monitoring period. The minimum recorded suspended sediment concentration ranged from

0.1 mg L^{-1} at sites 1 (Hunton) and 3 (Eaton) to 4 mg L^{-1} at site 2 (Broadward). The corresponding maximum ranged between 2407.8 mg L^{-1} at site 1 (Hunton) and 23784.9 mg L^{-1} at site 3 (Eaton). The highest mean (522.9 mg L^{-1}) and median (181.7 mg L^{-1}) suspended sediment concentrations were recorded at sites 5 (Lugwardine) and 4 (Marlbrook) respectively.

Table 4.5 Summary suspended sediment concentration data for the entire monitoring periods at each field site.

Statistic	Monitoring site				
	Hunton	Broadward	Eaton	Marlbrook	Lugwardine
Minimum (mg L^{-1})	0.1	4.0	0.1	0.2	1.0
Maximum (mg L^{-1})	2407.8	5876.1	23784.9	8435.8	11623.2
Median (mg L^{-1})	69.1	47.4	28.0	181.7	22.5
Mean (mg L^{-1})	113.7	209.4	174.6	383.6	522.9
Lower quartile (mg L^{-1})	28.0	32.1	23.4	107.0	8.8
Upper quartile (mg L^{-1})	124.1	205.9	75.9	338.7	95.0
Start	29/04/09	29/04/09	11/08/09	21/09/09	11/08/09
End	13/11/12	13/11/12	02/11/12	02/11/12	14/11/12

Figure 4.12 present histograms for the relative frequency of suspended sediment concentrations for each site over the entire monitoring period. At the Hunton monitoring site, suspended sediment concentrations < 25 mg L^{-1} represented 22.6% of the monitoring period, whereas concentrations < 100 mg L^{-1} represented 64.4%. Concentrations between 51-100 mg L^{-1} were the most dominant, representing 26.1% of the entire monitoring period. Only 1% of the period was represented by > 1000 mg L^{-1}, with 0.6% represented by concentrations between 1501-2000 mg L^{-1}. Similarly, suspended sediment concentrations < 25 mg L^{-1} and < 100 mg L^{-1} represented 18.5 and 68.1% of the monitoring period at the Broadward site (Figure 4.12). However, the concentrations between 26-50 mg L^{-1} dominated the monitoring period (33.9%), suggesting an increase in the proportion of the monitoring period characterised

by sediment concentrations < 50 mg L^{-1} for this site relative to the corresponding records for Hunton. Concentrations > 1000 mg L^{-1} represented 2.1% of the period, with over half of this being represented by concentrations between 3501-5000 mg L^{-1}, suggesting that the lower reaches of the River Arrow are characterised by higher episodic sediment concentrations in comparison to the upper parts of the catchment.

At the Eaton monitoring site, suspended sediment concentrations < 25 mg L^{-1} represented 46.4% of the monitoring period, whereas concentrations < 100 mg L^{-1} represented 83.5% (Figure 4.12). Concentrations between 16-25 mg L^{-1} and 26-50 mg L^{-1} were the most dominant, representing 19.1 and 17.1% of the entire monitoring period respectively.1.7% of the period was represented by concentrations > 1000 mg L^{-1}, with 0.6% represented by concentrations between 10001-25000 mg L^{-1}. In contrast, Marlbrook is dominated by concentrations between 101-500mg L^{-1} (62.7%). Suspended sediment concentrations < 25 mg L^{-1} only represented 1.9% of the monitoring period, whereas 7.3% of the period was represented by concentrations > 1000 mg L^{-1}. These comparisons suggest that there is a sustained increase in suspended sediment concentrations at the Marlbrook monitoring site relative to the Eaton site, although absolute maximum values for the latter site are greater (Table 4.5).

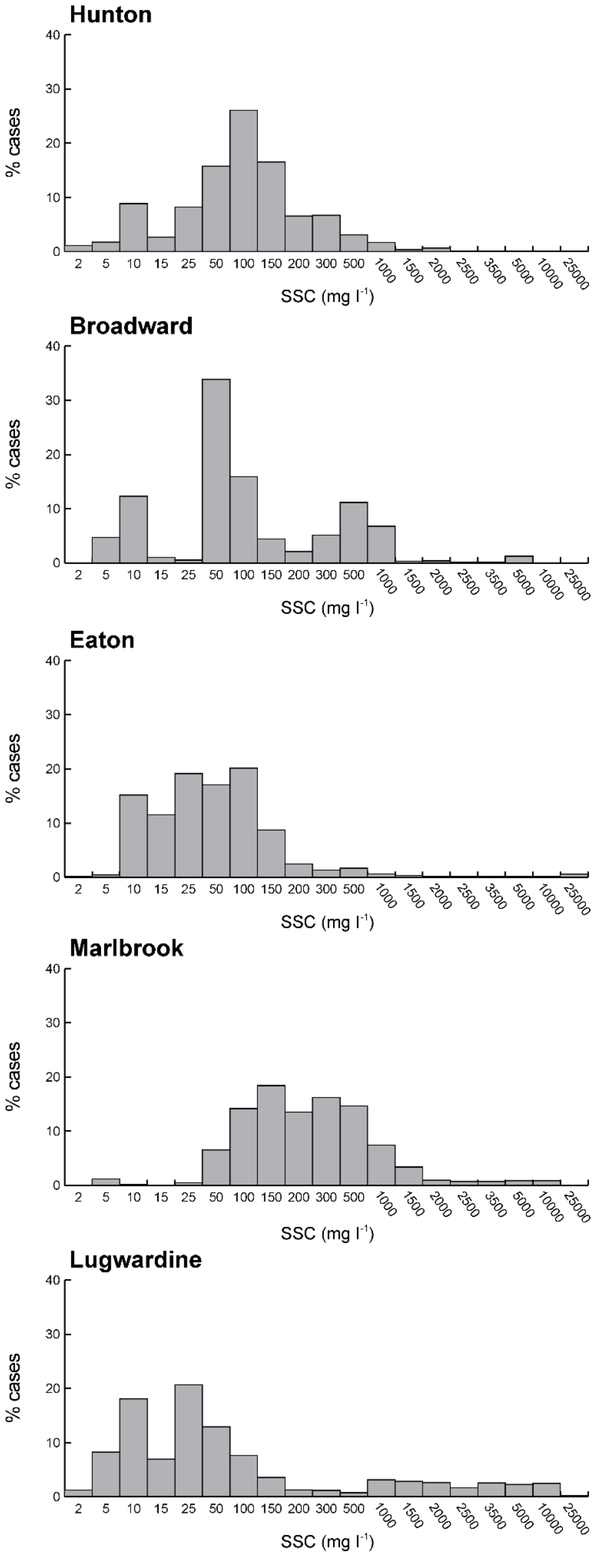


Figure 4.12 Suspended sediment concentration histograms for each field site over the entire monitoring period.

The relative frequency of suspended sediment concentrations at the Lugwardine monitoring site indicate that the majority (55.1%) of concentrations were < 25 mg L^{-1}. Concentrations < 100 mg L^{-1} represented 76.5% of the monitoring period (Figure 4.12). This would suggest a sustained reduction in the proportion of the monitoring period characterised by concentrations > 100 mg L^{-1} relative to the Marlbrook site. However, concentrations >1000 mg L^{-1} represented 14.5% of the entire monitoring period with 2.6% of the monitoring period being represented by concentrations >5000 mg L^{-1}. Therefore, this site has the highest mean concentrations (Table 4.5).

Table 4.6 presents summary statistics for the suspended sediment concentration data recorded at each monitoring site for the winter periods (October-March). The maximum values over the entire period of study, presented in Table 4.5, occur during the winter periods, whereas the minimum suspended sediment concentrations ranged between 0.4 mg L^{-1} at site 3 (Eaton) to 4.3 mg L^{-1} at site 2 (Broadward). The mean suspended sediment concentrations were higher during the winter periods ranging from 133.6 mg L^{-1} at site 1 (Hunton) to 528.2 mg L^{-1} at site 4 (Marlbrook). However, at site 5 (Lugwardine), the mean concentration during these periods were reduced. As with the entire period of study statistics, the maximum median suspended sediment concentration was recorded at site 4 (Marlbrook).

Table 4.6 Summary suspended sediment concentration data for the entire winter seasons (October-March) at each monitoring site.

Statistic	Monitoring site				
	Hunton	Broadward	Eaton	Marlbrook	Lugwardine
Minimum (mg L^{-1})	0.6	4.3	0.4	2.3	1.0
Maximum (mg L^{-1})	2407.8	5876.1	23784.9	8435.8	11623.2
Median (mg L^{-1})	74.1	54.0	29.2	174.3	20.3
Mean (mg L^{-1})	133.6	232.8	232.1	528.2	440.8
Lower quartile (mg L^{-1})	29.4	33.6	11.8	103.4	7.5
Upper quartile (mg L^{-1})	123.1	133.4	63.4	421.0	58.1

Figure 4.13 presents histograms for the relative frequency of suspended sediment concentrations for the winter months over the entire period of study. At the Hunton monitoring site, suspended sediment concentrations < 25 and < 100 mg L^{-1} represented 21.8 and 62.8% of the seasonal record. This is slightly less than what was recorded for the entire period of study, suggesting that suspended sediment concentrations were greater during the winter months. It is also notable that the winter period was represented by a greater proportion of extreme suspended sediment concentrations in comparison to the entire monitoring period, with 1.9% of the seasonal record > 1000 mg L^{-1} and 1.3% between 1501-2000 mg L^{-1}. At the Broadward monitoring site it was also evident that the winter period was represented by greater suspended sediment concentrations in comparison to the overall period of study. For example, suspended sediment concentrations < 25 mg L^{-1} represented 14.5% of the winter period compared to 18.5% of the entire monitoring period. Furthermore, concentrations > 1000 mg L^{-1} represented 3.5% of the period, with 2.3% represented by concentrations between 3501-5000 mg L^{-1} (Figure 4.13). This suggests that the higher suspended sediment concentrations in the lower reaches of the River Arrow occur during the winter period.

At the Eaton monitoring site, suspended sediment concentrations < 25 mg L^{-1} represented 43.0% of the seasonal record which is slightly lower than what was recorded for the entire period of study. However, concentrations < 100 mg L^{-1} represented a comparable 84.9% (Figure 4.13). 2.6% of the period was represented by concentrations > 1000 mg L^{-1}, with 0.8% represented by concentrations between 10001-25000 mg L^{-1}. This suggests that although the winter period is characterised by a greater proportion of concentrations < 100 mg L^{-1}, the extreme concentrations are higher. This pattern is especially highlighted at the Marlbrook monitoring site, where sediment concentrations < 100 mg L^{-1} were slightly higher than the entire monitoring period (24.0%). Furthermore, concentrations > 1000 mg L^{-1} represented 13.6% of the seasonal record, in comparison to 7.3% over the entire period of study.

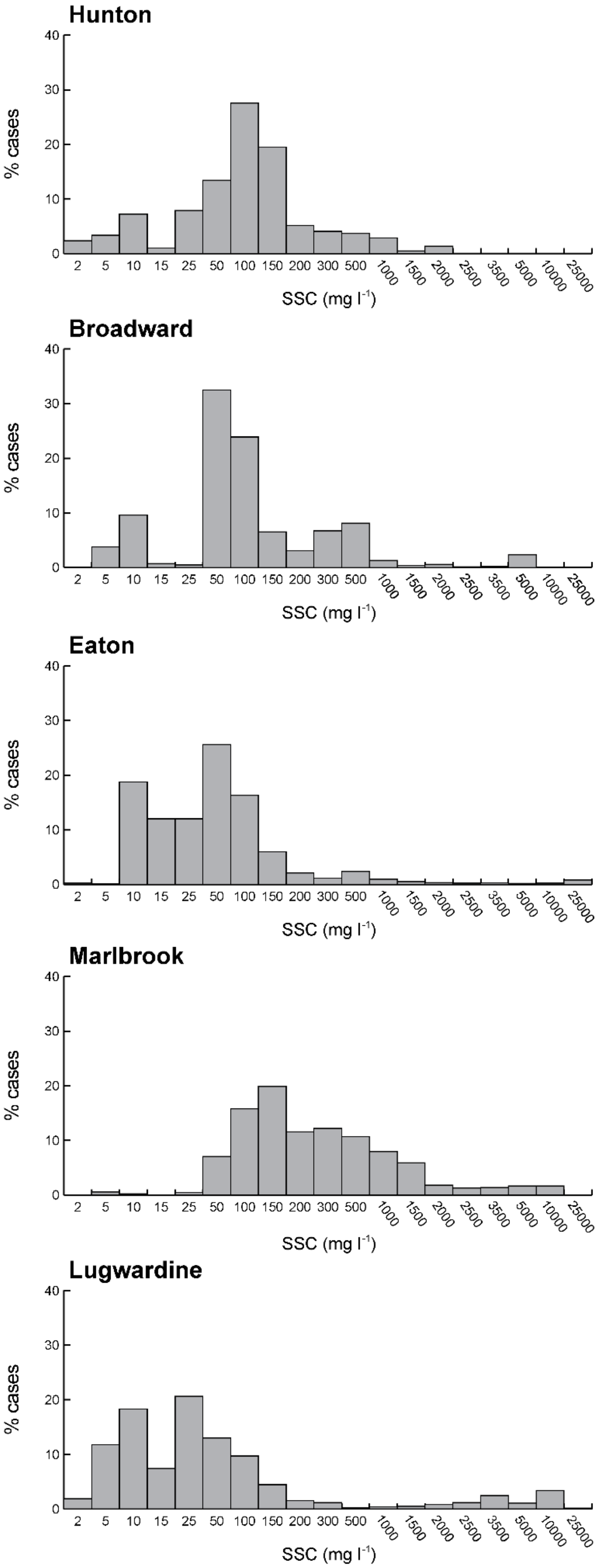


Figure 4.13 Suspended sediment concentration histograms for the winter seasons (October-March) over the entire monitoring period for each field site.

In contrast, the relative frequency of suspended sediment concentrations at the Lugwardine monitoring site indicate that the winter period is represented by greater < 25 mg L^{-1} concentrations (60.0%) in comparison to the entire monitoring period (Figure 4.13). It is also evident that concentrations > 1000 mg L^{-1} represented 9.5% of the seasonal record, which is slightly less than what was recorded for the entire period of study, suggesting that suspended sediment concentrations were lower during the winter months, with a reduced mean concentration (Table 4.6). However, the occurrence of the very extreme suspended sediment concentrations (>5000 mg L^{-1}) increased during the winter season, representing 3.5% of the seasonal record.

Summary statistics for the suspended sediment concentration data recorded at each monitoring site for the summer periods (April-September) are shown in Table 4.7. It is evident that there is a reduction in the maximum suspended sediment concentrations at each site during the summer relative to the corresponding records for the winter months. The minimum values over the entire period of study, presented in Table 4.5, also occur during the summer periods, suggesting a reduction in sediment concentrations during this period. Furthermore, the mean suspended sediment concentrations were notably lower in the summer compared to the winter period, with the exception of site 5 (Lugwardine).

Table 4.7 Summary suspended sediment concentration data for the entire summer seasons (April-September) at each monitoring site.

Statistic	Monitoring site				
	Hunton	Broadward	Eaton	Marlbrook	Lugwardine
Minimum (mg L^{-1})	0.1	4.0	0.1	0.2	1.0
Maximum (mg L^{-1})	2407.8	4866.1	15455.0	2034.9	11485.1
Median (mg L^{-1})	65.4	41.1	25.4	188.1	24.4
Mean (mg L^{-1})	97.5	187.4	117.8	235.1	592.9
Lower quartile (mg L^{-1})	27.1	30.7	16.0	114.4	11.2
Upper quartile (mg L^{-1})	128.4	341.8	84.1	308.8	332.0

Figure 4.14 presents histograms for the relative frequency of suspended sediment concentrations for the summer months over the entire period of study. There is a seasonal contrast in suspended sediment concentrations at the Hunton monitoring site, with lower concentrations evident during the summer months. For example, suspended sediment concentrations < 25 and < 100 mg L^{-1} represented 23.3 and 65.8% of the summer seasonal record, compared to corresponding records of 21.8% and 62.8% during the winter. It is also notable that the summer period was represented by fewer extreme suspended sediment concentrations relative to the corresponding records during the winter months, with only 0.3% of the seasonal record > 1000 mg L^{-1}. This seasonal contrast is more notable at the Broadward monitoring site where suspended sediment concentrations < 25 mg L^{-1} represented 22.3% of the summer period compared to 14.5% of the winter record. Furthermore, concentrations > 1000 mg L^{-1} only represented 0.8% of the period (Figure 4.14), whereas these suspended sediment concentrations represented 3.5% of the winter period. This suggests that the suspended sediment concentrations are generally lower during the summer.

A similar trend is also evident for the Eaton monitoring site, where suspended sediment concentrations < 25 mg L^{-1} represented 49.6 % of the seasonal record compared to the corresponding winter record of 43.0%. However, < 100 mg L^{-1} concentrations were marginally lower during the summer period relative to the corresponding records for the winter season. Nevertheless, there is a notable reduction in the frequency of > 1000 mg L^{-1} concentrations during the summer period, with only 0.3% represented by concentrations between 10001-25000 mg L^{-1} (Figure 4.14). This seasonal contrast at the Marlbrook monitoring site is highly evident, with 92.2% of the summer period represented by suspended sediment concentrations between 0-500 mg L^{-1}, compared to the corresponding 78.4% of the winter season. Furthermore, concentrations > 1000 mg L^{-1} represented only 0.9% of the seasonal record, in comparison to 13.6% during the winter months.

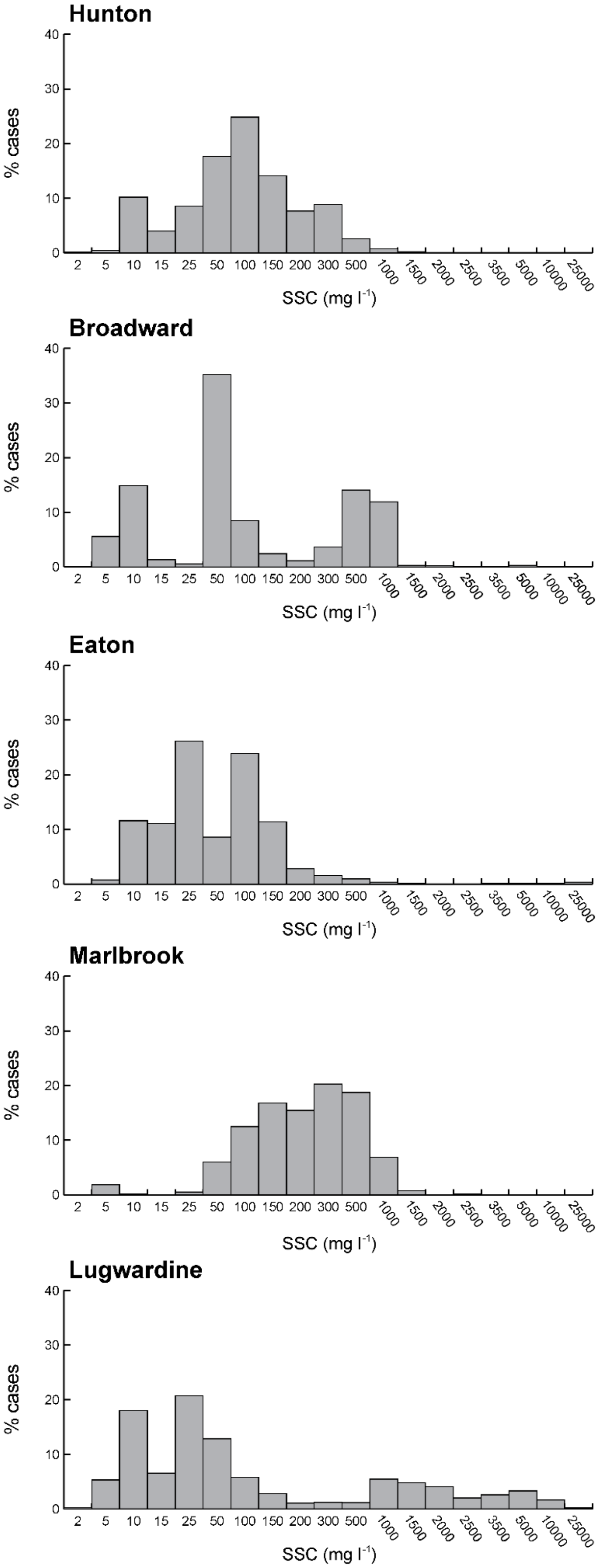


Figure 4.14 Suspended sediment concentration histograms for the summer seasons (April-September) over the entire monitoring period for each field site.

In contrast, this seasonal trend is reversed at the Lugwardine monitoring site. The relative frequency of suspended sediment concentrations at the Lugwardine monitoring site (Figure 4.14) indicate that 18.7% of the summer period is represented by concentrations > 1000 mg L^{-1}. This is nearly double that reported in the winter season. Furthermore, a reduction in the occurrence of suspended sediment concentrations < 100 mg L^{-1} relative to the corresponding records for the winter period is evident, suggesting that suspended sediment concentrations were higher during the summer months.

4.4.3 Suspended Sediment Yields

Daily suspended sediment fluxes were calculated using the following formula detailed in Horowitz (2003):

$$Suspended\ sediment\ flux\ (t\ day^{-1}) = [Q][SSC][0.0864]$$

Where *Q* is discharge in m^{3} s^{-1} and *SSC* the suspended sediment concentration in mg L^{-1}.

Specific suspended sediment yields were calculated by summing the daily sediment loads for each hydrological year (October to September inclusive) over the entire period of study (Table 4.8). The average annual specific suspended sediment yield for site 1 (Hunton) was 136 t km^{-2} yr^{-1}, ranging from 69 t km^{-2} yr^{-1} during the 2010-11 hydrological year to 182 t km^{-2} yr^{-1} during the 2009-10 hydrological year. The respective average total load was 17,636 tonnes, ranging from 8,875 to 23,853 tonnes. The average annual specific suspended sediment yield at site 3 (Broadward) was 208 t km^{-2} yr^{-1}, ranging from 66 t km^{-2} yr^{-1} during the 2009-10 hydrological year to 303 t km^{-2} yr^{-1} during the 2011-12 hydrological year. The respective average total load was 60,014 tonnes, ranging from 18,915 to 87,442 tonnes.

An average annual specific sediment yield of 170 t km^{-2} yr^{-1} was calculated for site 3 (Eaton), ranging from 61 t km^{-2} yr^{-1} during the 2010-11 hydrological year to 236 t km^{-2} yr^{-1} during the 2009-10 hydrological year. The average total load was calculated as 61,943 tonnes and ranged between 22,317 and 86,101 tonnes. At site 4 (Marlbrook), directly downstream of the Arrow confluence, the average annual specific sediment yield was calculated as 160 t km^{-2} yr^{-1}, ranging from 95 to 288 t km^{-2} yr^{-1} during the 2011-12 and 2010-11 hydrological years respectively. The respective average total load was 107,543 tonnes, ranging from 64,303 to 193,601 tonnes. The average annual specific suspended sediment yield at the final site (Lugwardine) was 173 t km^{-2} yr^{-1}, ranging from 11 t km^{-2} yr^{-1} during the 2009-10 hydrological year to 476 t km^{-2} yr^{-1} during the 2011-12 hydrological year. The average annual total load was greatest at this site (153,421 tonnes).

Table 4.8 Annual specific suspended sediment yield and total load data for each monitoring site.

Monitoring site	**Hydrological Year**	**Suspended sediment yield (t km^{-2} yr^{-1})**	**Total suspended sediment load (t)**
Hunton	2009-10	182	23,853
	2010-11	69	8,875
	2011-12	156	20,180
	Average	***136***	***17,636***
Broadward	2009-10	66	18,915
	2010-11	256	75,687
	2011-12	303	87,442
	Average	***208***	***60,014***
Eaton	2009-10	236	86,101
	2010-11	61	22,317
	2011-12	212	77,411
	Average	***170***	***61,943***
Marlbrook	2009-10	96	64,726
	2010-11	288	193,601
	2011-12	95	64,303
	Average	***160***	***107,543***
Lugwardine	2009-10	11	9,704
	2010-11	33	29,260
	2011-12	476	421,299
	Average	***173***	***153,421***

Figure 4.15 illustrates the spatial pattern of average annual specific suspended sediment yields calculated for each monitoring site. It is evident that there is

considerable variation in the suspended sediment yield at the two sites on the River Arrow. The upper Arrow site (Hunton) has the lowest suspended sediment yield (136 t km^{-2} yr^{-1}), whereas the average annual sediment yield at the lower reaches of the Arrow (Broadward) is much higher (208 t km^{-2} yr^{-1}). There is less variation in average annual suspended sediment yields at the three River Lugg sites, which all have lower average yields relative to the lower Arrow. A greater average annual suspended sediment yield is calculated for Eaton above the Arrow confluence (170 t km^{-2} yr^{-1}) compared to Marlbrook situated downstream of the confluence (160 t km^{-2} yr^{-1}). Given that the greatest sediment yields are calculated for the Arrow, this is surprising and could indicate that complex transportation and depositional factors in additional to sediment supply are at play. For example, the River Lugg becomes more incised and is characterised by greater discharges downstream of the Arrow confluence, which has the effect of diluting fine sediment (Bača, 2008). However, it is evident that this site is associated with a greater total load. Therefore, the decrease in specific annual suspended yields are more likely to be due to the greater drainage area directly downstream of the Arrow confluence. The lower Lugg (Lugwardine) has the greatest average annual suspended sediment yield of all three Lugg sites (173 t km^{-2} yr^{-1}) and is also associated with the greatest total load, suggesting a progressively sustained increase in fine sediment in the Lugg catchment.

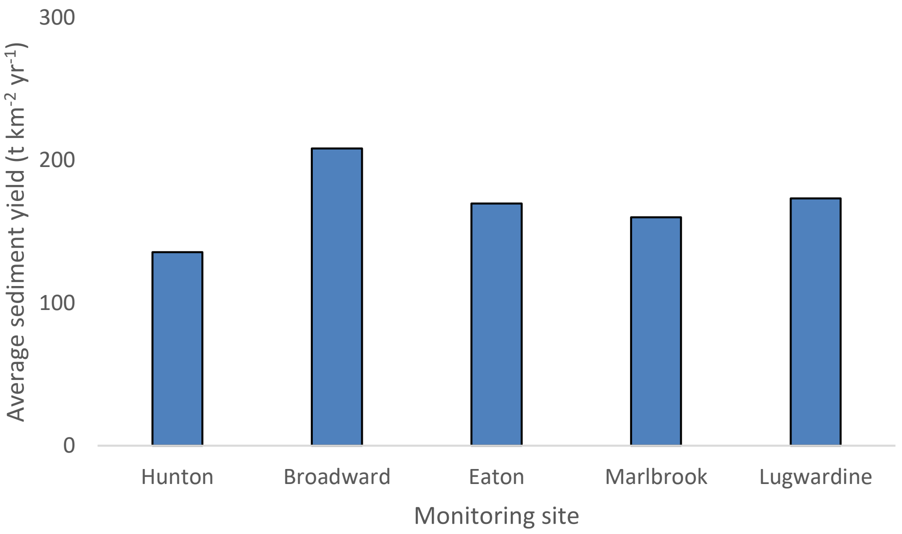


Figure 4.15 Average annual specific sediment yields over the three hydrological years at each monitoring site.

4.4.4 Summary

The suspended sediment flux has been calculated at each monitoring site through site-specific stage-discharge and turbidity-suspended sediment concentration rating relationships. There is considerable spatial variation in suspended sediment concentrations at each monitoring site. Average suspended sediment concentrations over the entire period of study range between 113.7 mg L^{-1} at site 1 (Hunton) and 522.9 mg L^{-1} at site 5 (Lugwardine). This pattern appears to concur with the substrate quality assessed in section 4.3. Episodic high sediment concentrations are evident at all sites, particularly at site 3 (Eaton), with maximum concentrations estimated to be > 10000 mg L^{-1}. However, these values are sporadic and only represent 0.6% of the entire monitoring period. There is however, an increase in suspended sediment concentrations downstream of the Arrow confluence at sites 4 (Marlbrook) and 5 (Lugwardine). There are also seasonal variations, with higher average suspended sediment concentrations associated with the winter period at all sites, with the exception of site 5 (Lugwardine). The greatest seasonal contrast is evident at site 4 (Marlbrook), with mean suspended sediment concentrations ranging from 235.1 mg L^{-1} in the summer to 528.2 mg L^{-1} in the winter for the entire monitoring period.

In addition, there are considerable spatial variations in average specific suspended sediment yields at the monitoring sites. This is most notable at the sites on the River Arrow, with the greatest yield associated with the lower parts of this catchment (Broadward, 208 t km^{-2} yr^{-1}). There is less variation in specific suspended sediment yields at the sites on the River Lugg, but it is evident that there is a progressively sustained increased in sediment loads further downstream, culminating at site 5 (Lugwardine). At this site, there is an average annual suspended sediment yield of 173 t km^{-2} yr^{-1} and an associated average sediment load of 153,421 tonnes.

4.5 Suspended Sediment Dynamics

The continuous monitoring of suspended sediment concentrations at each monitoring site enabled an analysis into the characteristics of the suspended sediment load variability during individual flow events. Previous research suggests that within-storm suspended sediment behaviour is dependent on a combination of factors comprising the interactions with flow, sediment supply from dominant sources and the availability of sediment in the channel including differences in sediment availability at the beginning and end of a flood event (Walling and Webb, 1982; Steegen *et al*., 2000; Steegen and Govers, 2001; Hudson, 2003). These interactions and changes in sediment availability during storm events result in hysteresis loops (Asselman, 1999) which have been classified into five classes (Williams, 1989).

The relationships between discharge and suspended sediment concentration and the resulting sediment delivery processes were therefore analysed for a number of different flow events of varying magnitude over the period of study (Figures 4.16-19). It is evident that there is considerable variability in the behaviour of within-storm suspended sediment in the Lugg catchment, suggesting that sediment supply and transport processes are not uniform. For example, Figure 4.14 illustrates a clockwise hysteresis (class II) relationship at the Hunton monitoring site, where the peak in suspended sediment occurs slightly prior to the flood peak. Suspended sediment is higher on the rising limb of the hydrograph compared to the falling limb which suggests rapid delivery of sediment sources early in the discharge event followed by sediment exhaustion (Lloyd *et al*., 2016). When considering the full hydrograph, it is evident that this event followed a period of relatively low flow during the winter season. Within-channel sediment is likely to be stored on the bed during these ‘non-event’ conditions and is subsequently readily available during an event of sufficient transport capacity. Therefore, the dominant sources in this event reflect the availability of within-channel sediment or adjacent areas located close to the monitoring site, with the availability of this material decreasing during the event (Lenzi and Lorenzo, 2000; Goodwin *et al.,* 2003). A subsequent pulse of suspended sediment is evident during the falling limb of the hydrograph, indicating a shift in the likely source of sediment. During this time, the flood event reached the capacity to transport sediment derived from surface runoff from more distant parts of the catchment.

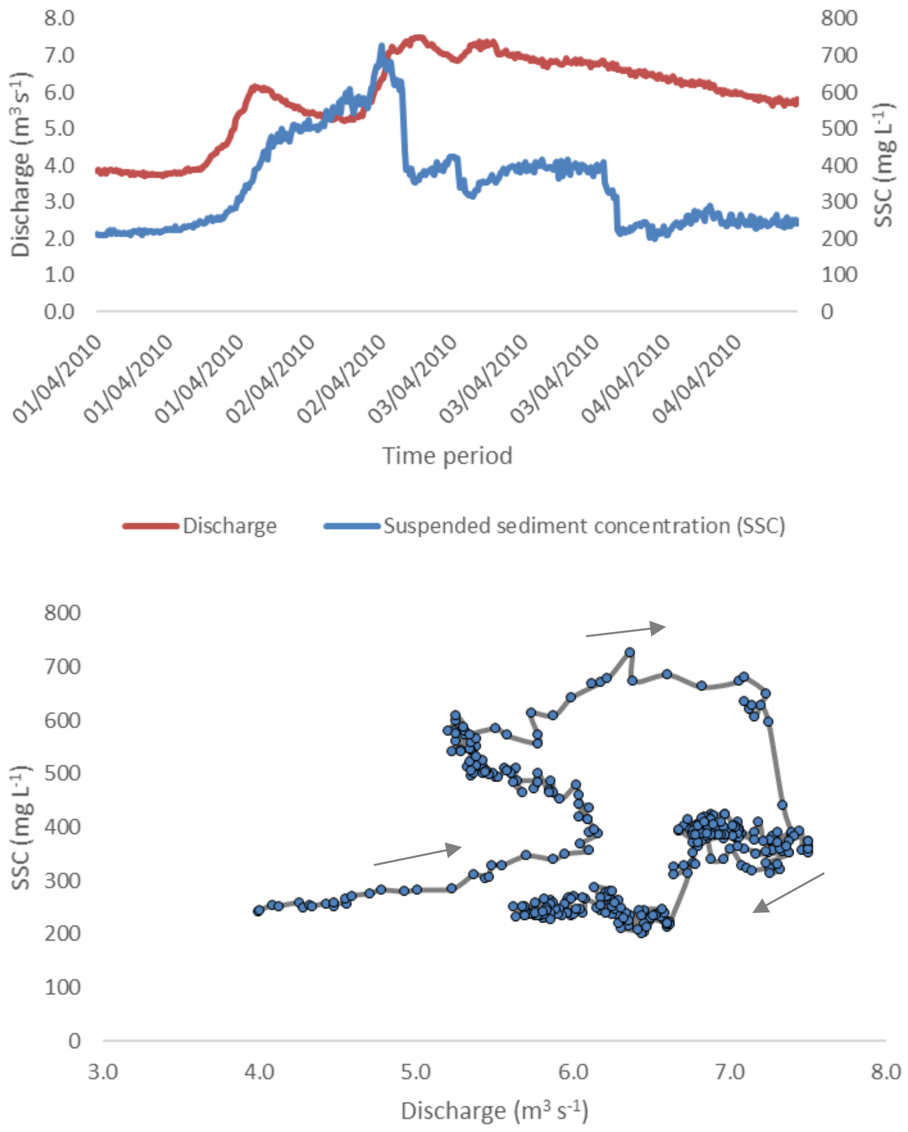


Figure 4.16 The relationship between suspended sediment and discharge during the 01/04/2010-04/04/2010 flood event at the Hunton monitoring site showing clockwise hysteresis.

Figure 4.17 illustrates an anti-clockwise (class III) relationship at the Lugwardine monitoring site, where the sediment peak lags the discharge suggesting that sediment may take a prolonged time to reach the monitoring site. The high flood magnitude had sufficient capacity to transport sediments from the upstream parts of the catchment. This indicates that sediment sources are likely to be generated from upstream sections of the catchment without being rapidly exhausted during the event (Oeurng *et al*., 2010). Therefore, within-channel sources are less important during these events. The high catchment wetness during the winter months coupled with the high soil erodibility in the catchment suggests that sediment could also originate from processes with slow dynamics, like for example, channel bank collapse (Williams, 1989). This could explain the larger secondary concentration peak during this event which coincided with lower discharge.

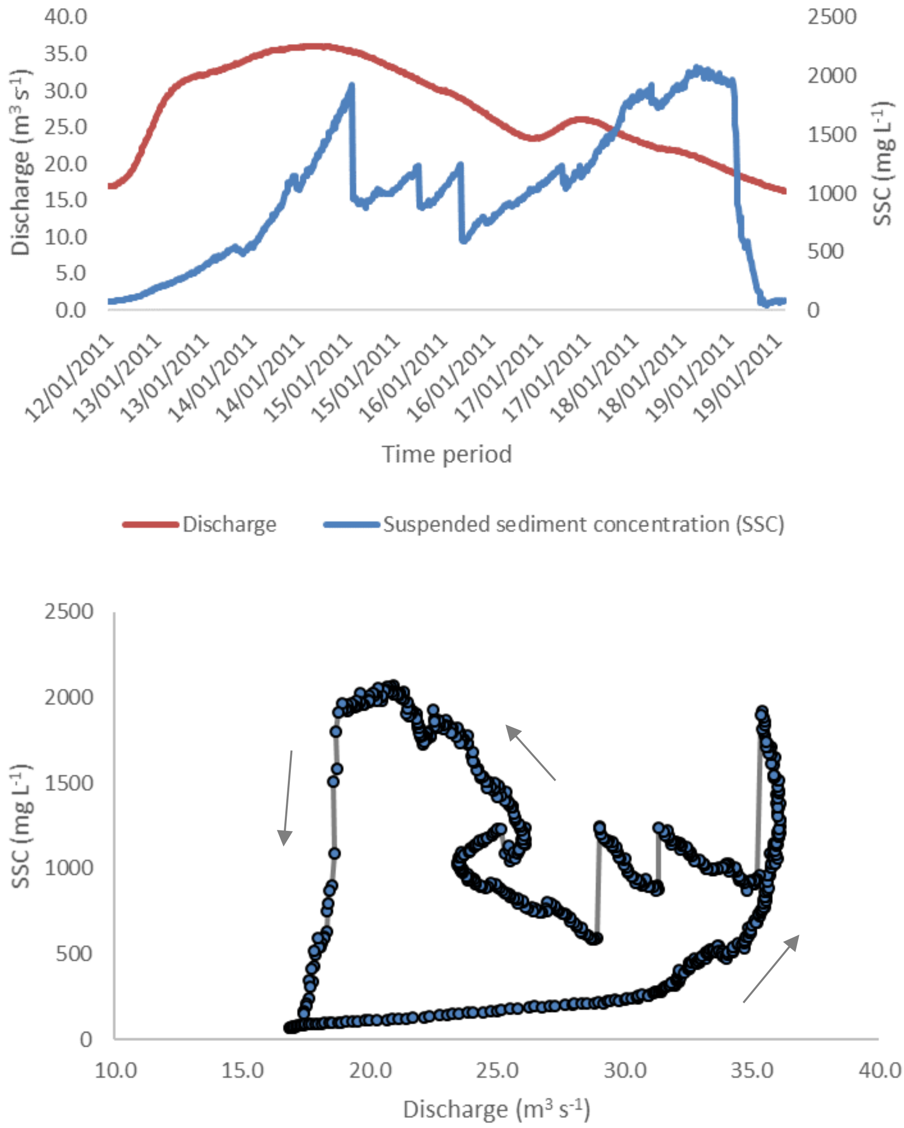


Figure 4.17 The relationship between suspended sediment and discharge during the 12/01/2011-19/01/2011 flood event at the Lugwardine monitoring site showing anti-clockwise hysteresis.

Figure 4.18 and 4.19 illustrate complex hysteresis patterns with a mixture of clockwise and anti-clockwise loops, interspersed with single-valued lines. These complex patterns can be caused by a shift in the relationship between discharge and suspended sediment concentration (Lloyd *et al.,* 2016). For example, at the Marlbrook monitoring site a number of flow and suspended sediment peaks are evident during a high magnitude summer flood event (Figure 4.18). It is evident that the first clockwise hysteresis loop, where the peak in suspended sediment occurs slightly prior to the flow peak is followed by a single-valued line (Class I), where the increase and decrease of discharge and suspended sediment are synchronised. This is associated with mobilisation and transport of sediment with an unrestricted supply. The initial flush and resulting exhaustion of sediment associated with clockwise hysteresis, followed by this unrestricted supply suggests a shift in the dominant sources of sediment. It is likely that within-channel sources were dominant at the beginning of the flood event, which were quickly flushed through the system. The further increase in discharge associated with heavy rainfall increased the capacity to transport sediments from the upstream parts of the catchment. This indicates that the associated peak of suspended sediment could originate from coarser deposited sediment mobilised from channel or bank erosion (Hudson, 2003). The largest peak in suspended sediment was associated with further high intensity rainfall falling on saturated ground. Sources during this peak therefore reflected soil erosion and surface runoff from areas located close to the monitoring site which was quickly flushed through the system. A further small pulse of suspended sediment is evident during the falling limb of the hydrograph, characterised by an anti-clockwise hysteresis relationship. This indicates a further shift in the likely source of sediment which could be attributed to bank collapse owing to the sustained magnitude of the event.

Figure 4.19 further illustrates this complex relationship during a winter flood event at the Marlbrook monitoring site. The first sediment peak lags the discharge peak and shows an anti-clockwise hysteresis relationship. The preceding winter events would have already flushed sediment through the system, so it is likely that within-channel storage would have been exhausted prior to this event. Therefore, sediment sources originate from upstream areas. This is followed by an unrestricted supply of sediment where the peak in suspended sediment matches the peak in discharge. A final clockwise hysteresis loop is evident, where material generated in the previous rainfall events is quickly flushed through the system before it becomes diluted with the peak in discharge.

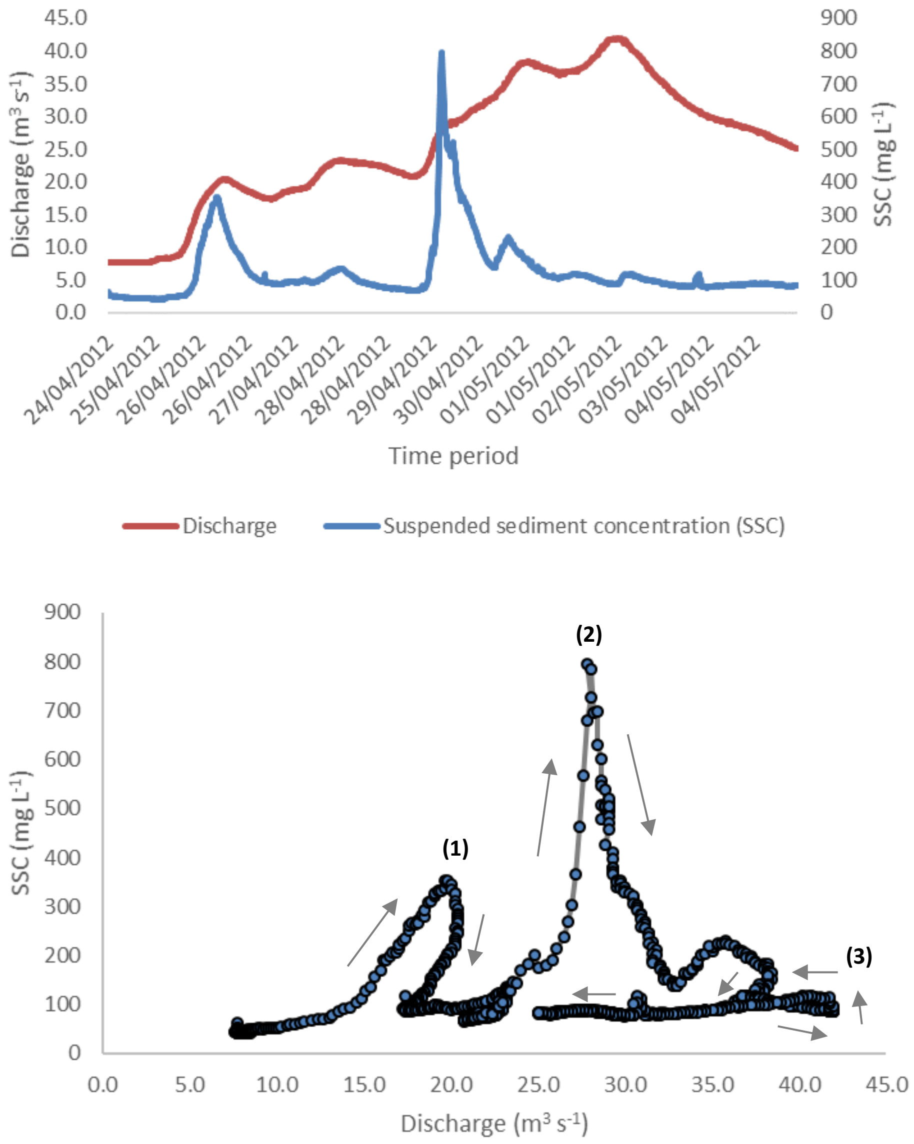


Figure 4.18 The relationship between suspended sediment and discharge during the 24/04/2012-05/05/2012 flood event at the Marlbrook monitoring site showing complex hysteresis.

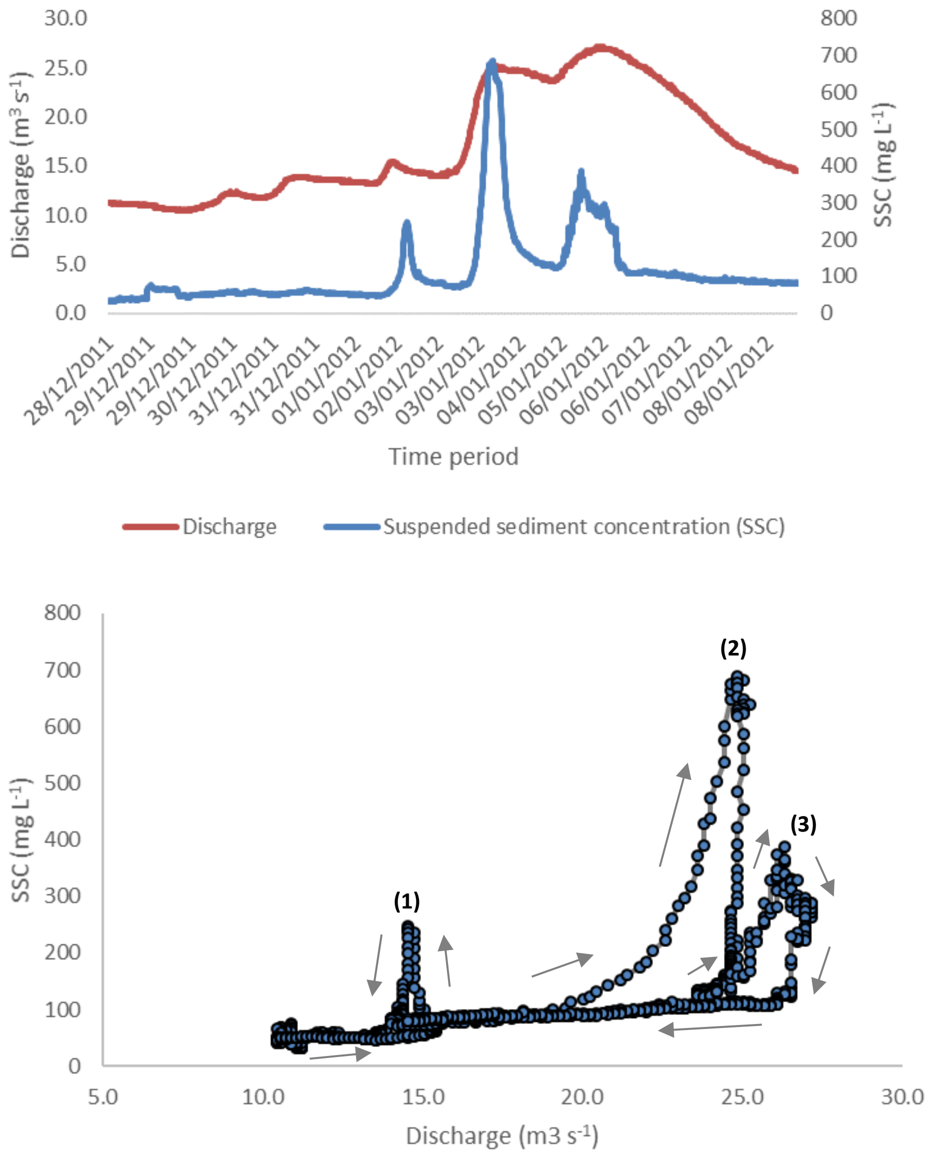


Figure 4.19 The relationship between suspended sediment and discharge during the 28/12/2011-08/01/2012 flood event at the Marlbrook monitoring site showing complex hysteresis.

4.6 Discussion

The monitoring of suspended sediment at the five sites in the Lugg catchment has provided a continuous record of suspended loads and has enabled the patterns of fine sediment movement to be assessed. Enhanced sediment loadings have been identified as a primary cause of the degradation of salmonid spawning gravels (Turnpenny and Williams, 1980; Theurer *et al*., 1998; Naden *et al*., 2003; Berry *et al*., 2003; Greig *et al.,* 2005). Past research has therefore recognised the effects of fine sediment infiltration and accumulation on the survival and health of salmonid populations. Early lab studies focused on particle size characteristics as determinants of emergence success. For example, particle size, in particular the percentage of fines and size composition of < 2 mm and < 1 mm, has been found to be important in determining egg survival and alevin health through the reduction of intragravel flow and dissolved oxygen (Heywood and Walling, 2007). Milan *et al.,* (2000) reported that where < 2 mm sediment exceeds 15 ± 5% of the channel bed material, salmonid embryo survival reduces to less than 50%. The assessment of the substrate quality established that this threshold is exceeded at each monitoring site, although only marginally at the Hunton site (Figure 4.20). This suggests that the gravel substrate quality is greatest in the upper parts of the Arrow catchment, whereas the lower parts of the Arrow and Lugg catchments have unfavourable salmonid spawning conditions. This is consistent with the findings by McEwen *et al*., (2012), who reported that over 20% of the substrate at downstream sites on the Arrow consisted of < 2 mm material. However, the gravel substrates were only sampled once during low flow conditions to establish the baseline grain-size distribution of the subsurface gravels.

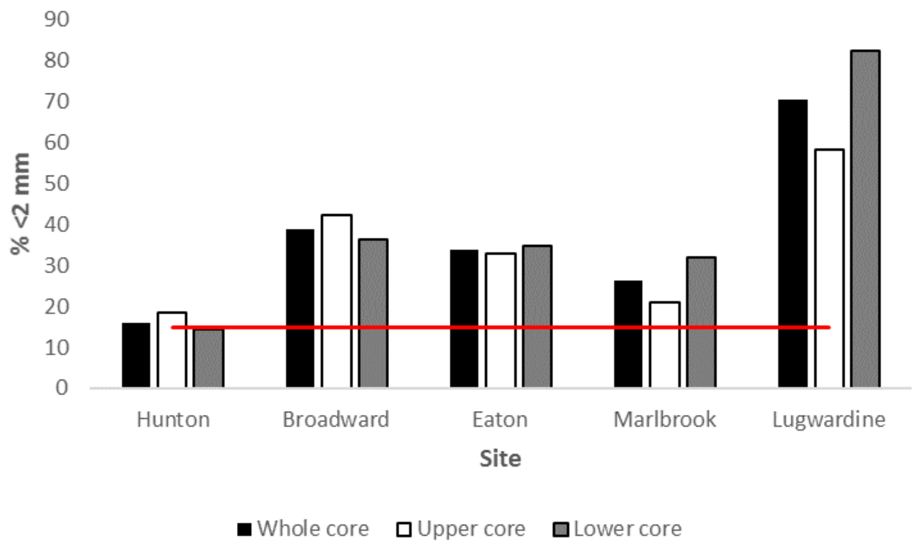


Figure 4.20 Comparison of matrix (< 2 mm) concentrations in gravel substrate sampled at each monitoring site, with threshold identified by Milan *et al*. (2000).

The average d_{50} of the suspended sediment collected during this study at each monitoring site ranged between 13.8 and 23.6 µm. These values are coarser to those cited by Walling *et al*., (2000) for rivers in the Humber and Tweed catchments, UK, where the d_{50} ranged between 4 and 14 µm. Walling and Moorehead, (1989) reported d_{50} values of > 100 µm for rivers throughout the world. The proportion of < 63 µm material collected at each site ranged between 97.2 to 98.6%, which is much higher than what was reported by Walling and Moorehead (1989) in global rivers. Therefore, the suspended sediment transported in the Lugg catchment would appear to be relatively fine.

Despite the fine-grained nature of the suspended sediment, samples collected at the monitoring sites reflect spatial and temporal variability, related to flood magnitude and sediment supply. There is considerable variation in suspended sediment particle size characteristics between sites. The suspended sediment transported through the catchment is the finest at site 5 (Lugwardine) and coarsest at site 1 (Hunton). This variation suggests that catchment characteristics, such as soil type, geology and land use, exert a significant influence on particle size characteristics of suspended sediment (Walling *et al.,* 2000). For example, the suspended sediment at site 1 (Hunton) is appreciably coarser than that at other sites (Table 4.4). This site is located in the upper parts of the Arrow catchment which is underlain by a geology and soil type less susceptible to water erosion, whereas the other sites are underlain by Old Red Sandstone bedrock and are particularly erodible during heavy rainfall events (see Chapter 2, section 2.4). Furthermore, spatial variation in particle size composition can reflect both the nature and relative importance of sediment sources within a catchment. For example, Walling *et al*. (2000) reported that sediment mobilised from the catchment surface may be finer than that mobilised from channel bank sources. The coarser suspended sediment at site 1 (Hunton) would suggest that channel bank sources play a pivotal role in the suspended sediment flux at this site, which is located in the headwaters and characterised by steep channel banks and a flashy flow regime (see Figure 4.1 for rainfall and flow characteristics at this monitoring site). This is particularly evident between sampling periods 11 and 14 (March – September 2011), which were associated the coarsest d_{50} values (Table 4.5). A bank protection scheme (Figure 4.21) was undertaken at Hunton Bridge just upstream of the monitoring site during 2011. Phase 1 of this work entailed base establishment with coarse sand and gravel which was undertaken during this summer period. The second phase involved in-filling the bank with fine soil which occurred between November and

December 2011. This can be directly related to the variation in suspended sediment collected at this monitoring site over this period. For example, Phase 1 coincided with low flow capacity of the channel owing to low intensity summer rainfall events. When considering the magnitude and intensity of precipitation throughout individual sampling periods, it is evident that the lowest intensity rainfall over the whole monitoring period occurred during these sampling periods (Figure 4.22). Therefore, flow events were more likely to transport this coarser sediment than surface runoff from upstream sources. Phase 2 coincided with early winter rainfall, where this fine un-consolidated sediment was easily transported during the higher magnitude events (Figure 4.22). As a result, the d_{50} values of the suspended sediment collected during these events were much finer and the amount of sediment collected in the time-integrated samplers were much greater (Table 4.5).

Figure 4.21 Bank protection scheme at Hunton Bridge, just upstream of monitoring site (a) evidence of bank erosion undermining bridge 18th November 2009, (b) phase 1 base establishment 15th November 2011, (c) phase 2 bank in-filling 13th December 2011, (d) consolidated bank with erosion evident 4th June 2012.

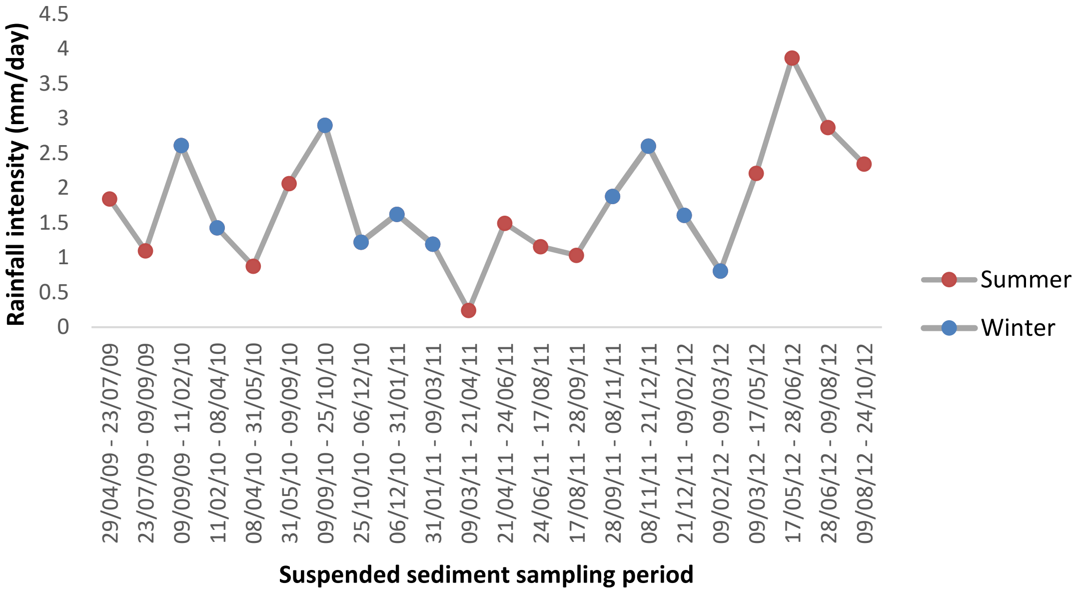


Figure 4.22 Rainfall intensity associated with each sampling period at the Hunton monitoring site *(Shobdon Airfield gauging station, Met Office 2013).*

The finer suspended sediment associated with the other sites could suggest a reduced contribution from channel bank sources. However, it is possible that the finer suspended sediment could reflect the re-working of sediment during different flow events. Sediment could be transported and deposited within the channel during particular flow events and re-mobilised during a preceding event where this material is collected as suspended sediment downstream. This was evident during a number of events exhibiting a clockwise hysteresis relationship between discharge and suspended sediment, where within-channel sediment is quickly flushed through the system and subsequently exhausted before peak discharge (Figure 4.16).

Furthermore, there is considerable variation in the quantity of suspended sediment collected over different sampling periods at the monitoring sites. The average amount of suspended sediment collected in the time integrated samplers is generally greatest during the winter months, except at site 3 (Eaton), where no seasonal differences were identified. Nevertheless, the highest quantities of suspended sediment are associated with high flow events (see Figure 4.1 and 4.2) suggesting that flow magnitude exerts a significant influence on suspended sediment.

This study has also identified persistently high sediment loadings within the Lugg catchment. Mean suspended sediment concentrations over the entire period of study ranged from 113.7 mg L^{-1} to 209.4 mg L^{-1} in the upper Lugg and Arrow catchment, whereas mean concentrations in the lower Lugg where higher and ranged between 383.6 mg L^{-1} to 522.9 mg L^{-1}. Episodic high suspended sediment concentrations are evident at all sites, with maximum values ranging from 2,407.8 mg L^{-1} at site 1 (Hunton) in the upper Arrow to 23,784.9 mg L^{-1} at site 3 (Eaton) in the upper Lugg. When comparing these high sediment loadings with other catchments in the UK, it is evident that the Lugg catchment has a fine sediment problem. For example, Worrall *et al*. (2013) estimated the suspended sediment flux for 270 catchments across the UK between 1974 and 2010 and reported a median suspended sediment concentration of 9 mg L^{-1} with lower and upper quartile figures of 2 mg L^{-1} and 65 mg L^{-1} respectively. The corresponding median values reported in the Lugg catchment range from 22.5 mg L^{-1} at the Lugwardine monitoring site to 181.7 mg L^{-1} at the Marlbrook monitoring site, whereas lower and upper quartile values range from 8.8 mg L^{-1} to 107 mg L^{-1} and 75.9 mg L^{-1} to 338.7 mg L^{-1} respectively (Table 4.5).

Nevertheless, the mean suspended sediment concentrations reported are consistent with a previous study by D'Aucourt (2004), who investigated the spatial and temporal variations in suspended sediment concentrations in the River Wye catchment between 1992 and 2003. Mean suspended sediment concentrations of 226.8 mg L^{-1} in the upper Lugg and Arrow catchments were reported. The two largest maximum values were also recorded in this part of the catchment, with a maximum of 19,646 mg L^{-1} in 2002. However, D'Aucourt (2004) reported that the lower parts of the Lugg catchment were associated with much lower suspended sediment concentrations (mean and maximum values of 29.5 mg L^{-1} and 2,816 mg L^{-1}). Nevertheless, the larger concentrations evident in the lower parts of the Lugg catchment in this study reflect the recent accelerated diffuse fine sediment pollution linked to changing land use and its management (see Chapter 1). Large amounts of easily erodible, fine friable red sandy soils are washed off the land during heavy rainfall events dramatically increasing the suspended sediment concentration (Figure 4.23).

Figure 4.23 High suspended sediment concentrations in (a) upper Lugg and (b) lower Lugg after high magnitude summer storm (28th June 2012).

The UK environmental standard for suspended solids was set by the Freshwater Fish Directive giving a guideline standard of an annual average of 25 mg L^{-1}. However, this Directive was repealed in 2013 by the WFD (see Chapter 1 section 1.3), and since then no environmental objective for this parameter has been specified. This followed the proposal by the UK Technical Advisory Group (UKTAG) that the guideline standard for suspended solids should not move directly into the definition of good ecological status under the WFD (UKTAG, 2008). The report stated that an annual mean is not appropriate for tackling occasional events such as run off from land and therefore recommended that a management approach should be taken which should consider the 95th-percentile in order to take into account the rarer but potentially damaging events. This would enable management and monitoring to be targeted at risk according to the type of land, time of year, rainfall and how the land is managed. However, since then no environmental guideline or imperative standard for suspended solids has been specified. Nevertheless, it is useful to put the results of this study in context with the repealed guideline standard and the UKTAG recommendation (Figure 4.24).

The relative frequency of suspended sediment concentrations at each site confirm very high sediment loadings, further confirming the sediment problem in the Lugg catchment. This is particularly evident in the Arrow catchment, with concentrations > 25 mg L^{-1} representing 77.4 and 81.5% of the entire monitoring period at Hunton and Broadward respectively. The River Arrow shows an evident influence on the relative frequency of suspended sediment concentrations at the sites on the River Lugg. For example, concentrations > 25 mg L^{-1} represent 53.6% of the entire monitoring period upstream of the confluence (Eaton), however, represent 98.1% downstream of the confluence (Marlbrook). In contrast, corresponding relative frequency of concentrations > 25 mg L^{-1} at the lower Lugg site (Lugwardine) represent 44.9% of the entire monitoring period. When considering the 95th-percentiles at each monitoring site it is evident that suspended sediment concentrations progressively increase further towards the catchment outlet (Figure 4.24). For example, the 95th-percentiles range from 214 mg L^{-1} at the Eaton monitoring site to 3,458 mg L^{-1} at the furthest downstream monitoring site (Lugwardine). Although there are no specific suspended sediment standards as part of the WFD, the concentrations in the Lugg catchment are consistently above the repealed guideline and are therefore likely to be above any standards that may be implemented in the future.

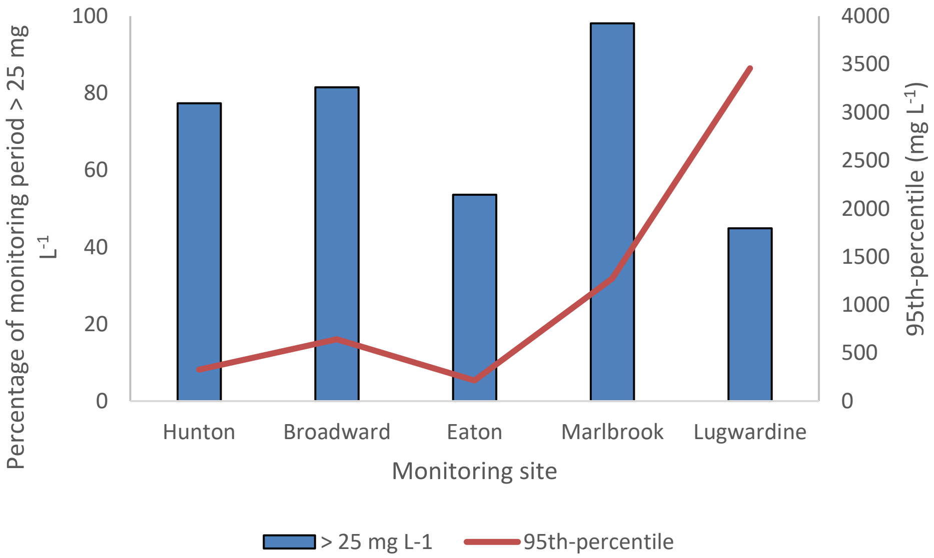


Figure 4.24 Relative frequency of suspended sediment concentrations > 25 mg L^{-1} and 95th-percentiles across the entire monitoring period at each site.

In addition, there are considerable spatial variations in average specific suspended sediment yields at the monitoring sites (Figure 4.14). This is most notable for the sites on the River Arrow, with the greatest yield associated with the lower parts of this catchment (Broadward, 208 t km^{-2} yr^{-1}). There is less variation in specific suspended sediment yields at the sites on the River Lugg, but it is evident that there is a progressively sustained increase in sediment loads further downstream, culminating at site 5 (Lugwardine). At this site, there is an average annual suspended sediment yield of 173 t km^{-2} yr^{-1} and an associated average sediment load of 153,421 tonnes. This suggests that the River Arrow it an important contributor of fine sediment in the Lugg catchment, with average total load calculated to be 60,015 tonnes.

It is evident that the suspended sediment yields in the Lugg catchment (Table 4.13) are relatively high when compared to other empirical evidence in the UK, further suggesting that the Lugg catchment has a fine sediment issue. Available empirical evidence suggests that suspended sediment yields across England and Wales range between < 1 t km^{-2} yr^{-1} and > 500 t km^{-2} yr^{-1} and are typically in the range of 40-50 t km^{-2} yr^{-1} (Walling and Webb, 1987). For example, Wass and Leeks (1999) have reported suspended sediment yields of 15 t km^{-2} yr^{-1} in the Humber catchment and sediment yields ranging between 23.9 t km^{-2} yr^{-1} and 67.6 t km^{-2} yr^{-1} have been reported in the Exe catchment (Harlow *et al.,* 2006). In addition, long term sediment yields in upland areas have been estimated to be 30 t km^{-2} yr^{-1} (Walling and Webb, 1987) and 50 t km^{-2} yr^{-1} (Newson and Leeks, 1985). In many instances these values are impacted by topography, land use and other human activities. Walling *et al.* (2007) collated 146 sediment yield estimates in UK catchments in order to assess and manage fine sediment inputs into freshwater ecosystems. They summarised that specific sediment yields in lowland agricultural catchments with catchment areas of 100-1000 km^2 ranged between 1 t km^{-2} yr^{-1} and 311 t km^{-2} yr^{-1} with an average sediment yield of 46 t km^{-2} yr^{-1}. For example, a continuous turbidity monitoring study in the River Tweed catchment between 1994 and 1997 calculated sediment yields of 311 t km^{-2} yr^{-1} (Bronsdon and Naden 2000), whereas a sediment yield of 174 t km^{-2} yr^{-1} was reported in the Avon catchment (Fleming, 1970).

Although the suspended sediment yields reported are relatively high compared to other yields reported in UK catchments, the values are generally consistent with other studies in the Lugg catchment. For example, Walling *et al*. (2002) estimated sediment yields ranging between 81.9 t km^{-2} yr^{-1} and 131 t km^{-2} yr^{-1} for two small sub-catchments in the Lugg. Furthermore, a study on salmon spawning habitat quality in the Lugg catchment (Burke, 2011) reported a specific sediment yield of 55.9 t km^2 at a site just upstream of Eaton for the period February-April 2008. Specific sediment yields for the same monthly period during this study at site 3 (Eaton) were calculated to range between 4.2 and 51.4 t km^2. Therefore, this suggests that although average sediment yields calculated in this study for different sites in the Lugg catchment are higher than the typical value for UK rivers identified by Walling and Webb (1987), they are consistent with other lowland agricultural rivers of similar catchment size.

4.7 Conclusion

This chapter has presented the spatio-temporal variations in suspended sediment delivered to key sites in the Lugg catchment. It is evident that there are considerable spatial variations in the substrate quality and suspended sediment characteristics at the monitoring sites. An assessment of the substrate gravel established that all sites had poor quality gravels exceeding the 15 ± 5% < 2 mm threshold identified by early studies (Milan *et al*., 2000). This is most notable for the lower Arrow (Broadward) and lower Lugg (Lugwardine) sites. The suspended sediment transported in the Lugg is relatively fine with more than 95% of the material < 63 µm. Although the average d_{50} values are coarser than what was reported in the Humber and Tweed catchments (Walling *et al.,* 2000), it is finer than other studies. Like with the substrate material, there is considerable variation in the characteristics of suspended sediment. For example, the suspended sediment characteristics get progressively finer at sites located further down the catchment.

In addition, there is considerable temporal variation in the particle size characteristics of suspended sediment collected during different flow events. It is notable that there are distinct seasonal influences, with finer material transported during the winter months at three of the five sites (Hunton, Eaton and Lugwardine). This trend is reversed at Broadward and Marlbrook, where finer material is transported during the summer period. However, there is less temporal variability associated with the suspended sediment collected at the two sites located in the lower parts of the Arrow and Lugg catchment (Broadward and Lugwardine). Furthermore, the quantity of suspended sediment collected in the time-integrated sediment samplers is generally greater during the winter, except at site 3 (Eaton), where the seasonal variation is marginal. This suggests that variations relate to differences in flood magnitude, which may disrupt the bed surface armour layer, and sediment supply from upstream sources.

Suspended sediment concentrations vary at each site with the greatest average (522.9 mg L^{-1}) over the entire period of study in the lower Lugg (Lugwardine). The relative frequency of concentrations > 25 mg L^{-1} represent 44.9% of the entire monitoring period at this site. Although the annual average suspended solids guideline standard of 25 mg L^{-1} under the EC Freshwater Fish Directive was repealed in 2013 by the Water Framework Directive, it was useful to put these findings into this context. This suggests that all sites in the Lugg catchment regularly exceed this value, particularly below the Arrow confluence (Marlbrook) where concentrations > 25 mg L^{-1} represent 98.1% of the entire monitoring period. Episodic high sediment concentrations are evident at all sites, particularly just above the Arrow confluence (Eaton), with a maximum concentration estimated to be > 10,000 mg L^{-1}. However, these values are sporadic and represent 0.6% of the entire monitoring period. This further emphasises the problem of high sediment loading in this catchment. There are also seasonal variations in suspended sediment concentrations, with higher average concentrations associated with the winter period at all sites, with the exception of Lugwardine. This may reflect the dilution during higher flows associated with the more incised channel morphology at this site.

Individual events displayed complex storm-specific interactions between discharge and sediment concentrations (Figures 4.16-19). These hysteresis relationships suggest variations in sediment supply and dominant source areas. For example, clockwise hysteresis loops were evident in flashy events where within-channel sources were readily available and flushed through the system before peak discharge. Anti-clockwise loops were also evident during higher magnitude events which had greater capacity to transport sediments from upstream sources without being rapidly exhausted during the event. Therefore, within-channel sources are less important during these events. These events were commonly associated with times of high catchment wetness and represented sources from surface runoff and processes with slow dynamics, for example, channel bank collapse. However, many events represented a complex interaction of hysteresis patterns with a mixture of clockwise and anti-clockwise loops, interspersed with single-valued lines, representing shifts in the dominant sources of sediment. Therefore, there are shifts in the form of the relationship between discharge and suspended sediment concentration during different events.

This chapter has also identified that there are considerable spatial variations in average specific suspended sediment yields at the monitoring sites. This is most notable at the sites on the River Arrow, with the greatest yield associated with the lower parts of this catchment (Broadward, 208 t km^{-2} yr^{-1}). There is less variation in specific suspended sediment yields at the sites on the River Lugg, but it is evident that there is a progressively sustained increase in sediment loads further downstream, culminating at site 5 (Lugwardine). At this site, there is an average annual suspended sediment yield of 173 t km^{-2} yr^{-1} and an associated average sediment load of 153,421 tonnes.

The River Arrow was identified as an important contributor of fine sediment in the Lugg catchment, with the average total load at Broadward calculated to be 60,015 tonnes. Although the effect of this site on average specific sediment yields upstream and downstream of the confluence is not noticeable, it is dramatically highlighted when considering the total loads at the respective sites. For example, the average total load upstream of the Arrow confluence (Eaton) was 60,943 tonnes, whereas the corresponding downstream figure was 107,543 tonnes at Marlbrook. The effect of the River Arrow on the sediment characteristics transported through the Lugg catchment was also highlighted through the particle size analysis, with finer d_{50} values associated upstream of this confluence compared to downstream. Nevertheless, the analysis of the substrate material showed that the downstream site had a smaller proportion of < 2 mm material in gravels compared to upstream. This suggests that the high sediment loads from the Arrow catchment are not deposited directly downstream in the River Lugg. Instead, this material is transported throughout the whole system causing increased suspended sediment concentrations at Marlbrook and Lugwardine.

However, it is important to note that suspended sediment concentrations and loads were calculated using suspended sediment-turbidity rating relationships (Figure 4.11). Although Lacour *et al.,* (2009) suggested that adequate relationships between concentration and turbidity can be established using this approach, issues associated with debris collection after large flow events or algae growth during the summer can result in data inaccuracy. Therefore, although field equipment was regularly checked and cleaned over the period of study, concentrations and subsequent suspended sediment yields may be over-estimated during these times. Intermittent probe failure will also cause an underestimation during these periods. As a result, caution must be applied when interpreting these loads and suspended sediment yields. Nevertheless, suspended sediment concentrations and sediment yields are consistent with other studies in the Lugg catchment (D’Aucourt, 2004, Burke, 2011) and other lowland agricultural rivers of similar catchment size (Bronsdon and Naden, 2000; Walling *et al*., 2007).

CHAPTER 5
STATISTICAL PROCEDURES AND FINGERPRINTING TECHNIQUE

5.1 Introduction

This chapter details the statistical procedure adopted in the fingerprinting technique used to identify sources of fine sediment within the Lugg catchment. The statistical discrimination methods used to identify the optimum fingerprint are explained, along with the application of the numerical mixing model that identifies sources and their relative contributions. An error calculation, assessing the reliability of source ascription is also detailed.

5.2 The Fingerprinting Approach

Traditionally, the sediment fingerprinting approach has involved the use of single diagnostic properties to discriminate potential sediment sources (Walling and Collins 2000; Collins and Walling 2002; 2004). However, this approach often creates a lack of dimensionality (Collins *et al*., 2009) and has been known to introduce spurious source-sediment matches (Walling *et al.,* 1993; Collins and Walling 2002). Dimensionality refers to the number of diagnostic properties in relation to the number of potential source types discriminated against. According to Lees (1994), a lack of dimensionality (i.e. fewer diagnostic properties than potential source types) can lead to groups of source samples that are ‘numerical multiples’ of one another. Recent fingerprinting studies have therefore exploited composite approaches that comprise several properties influenced by differing environmental controls from either a particular property subset or a combination of different subsets in order to satisfy dimensionality (e.g. Walling *et al*., 1993; Walling and Woodward 1995; Collins *et al.,* 1997c; 1998; Krause *et al.,* 2003; Collins *et al*., 2010b; Liu *et al*., 2016; Owens *et al*., 2016; Manjoro *et al*., 2017; Pulley *et al*., 2017; Zhang *et al*., 2017; Nosrati *et al.,* 2018; Tiecher *et al.,* 2018). Such fingerprints are identified by statistical verification and are used in conjunction with multivariate numerical mixing models (also referred to as un-mixing models) to provide quantitative information on sediment contributions from individual sources. Statistical and un-mixing model approaches have received increasing attention in the literature over recent years, with studies suggesting recent developments to the statistical framework to incorporate and report uncertainties and assessing the accuracy of different methods (e.g. Collins *et al*., 2010c; 2012b; Haddadchi *et al.,* 2014; Pulley *et al*., 2015; Lui *et al*., 2016; Owens *et al.,* 2016; Collins *et al.,* 2017). Composite fingerprints therefore provide the most robust, reliable and comprehensive approach to sediment source tracing (Owens *et al*., 2000; Walling *et al.,* 2002a). Maximising the number of properties used in the sediment fingerprinting analysis increases the dimensionality of the data and may potentially reduce uncertainty (Walden *et al*., 1997; Collins *et al.,* 2009).

However, as identified by Foster and Lees (2000), there are several assumptions that are applicable to sediment provenance studies concerning actively-transported fine sediments. For example, the sediment source fingerprinting technique assumes that the selected properties can discriminate between a minimum of two different sources within the catchment, and that the un-mixing models used to establish relative sediment source contributions, within known or predictable tolerances, are able to deal with variability in source properties. It also assumes that selective erosion and subsequent sediment delivery processes do not alter the particular fingerprint properties beyond what can be appropriately corrected for, and that the properties are readily transported and deposited in association with suspended sediment (Collins *et al.,* 2009; Laceby *et al.,* 2017).

It is therefore essential that the assumptions that underpin and place limitations on the application of fingerprinting studies are fully-recognised in order to reliably discriminate sources of fine sediment. For instance, tracer signatures could become altered during transport via chemical exchanges occurring between dissolved contaminants in the channel and the actively transported sediment (Zhang and Huang 1993; Foster *et al.,* 1996). Selective erosion and sediment transport could also transpire due to differences in grain size, as tracer properties are partially controlled by the particle size distribution of eroded and transported sediments (Komar *et al.,* 1989; Walling and He 1993; Oldfield and Yu 1994; Foster *et al.,* 1998; Foster and Lees 2000). This sorting effect of particles by size during detachment, mobilisation, transportation and depositional processes represents a key challenge to the assumptions made in sediment provenance studies (Koiter *et al*., 2013b; Belmont *et al*., 2014). As a result, two main approaches, which are often used in combination have been used to address particle size impacts on fingerprint properties (Laceby *et al*., 2017). These include fractionation of source and sediment material to a narrow particle size range (see Chapter 3, section 3.4), and the inclusion of grain size concentration correction factors during the application of the mixing model (see section 5.5.2). To mitigate differences in the particle size distributions of source and sediment material, fractionation is applied to minimise potential sorting induced differences between source and sediment properties (Laceby *et al.,* 2017). In order to directly compare source and sediment samples, further particle size corrections are necessary. These corrections are based on the assumption of a simple linear relationship between particle size and tracer signature, and more recently, the incorporation of a within-model weighting factor (Collins *et al.,* 2017).

The well-established fingerprinting approach adopted within this study, designed in part to evaluate assumptions and assess reliability is summarised in Figure 5.1.

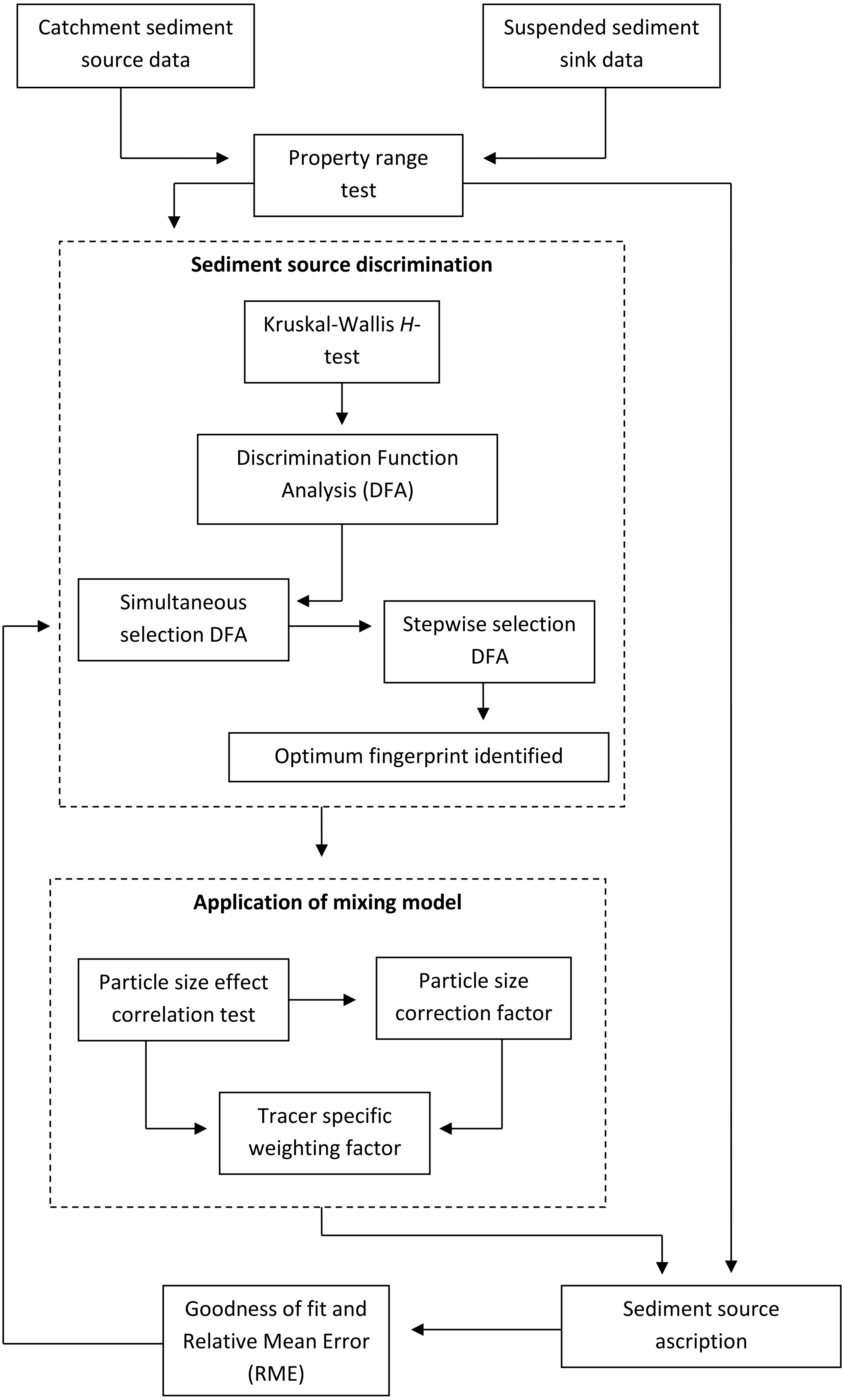


Figure 5.1 Fingerprinting approach adopted within this study.

Before the optimum composite fingerprints could be selected, the geochemical property concentration data measured using ICP-MS was first subjected to a property range test. This assessment ensured that the suspended sediment samples were represented by the potential source material. The next phase involved a two-stage discrimination procedure to identify composite fingerprints capable of representing individual source types within the catchment. A Kruskal-Wallis *H*-test and multivariate Discriminant Function Analysis (DFA) was utilised to statistically verify these signatures. The former test was used to examine the ability of individual properties to effectively distinguish inter-group contrasts, whereas the latter confirmed which of these properties offered the optimum source discrimination. The DFA process initially involved a simultaneous entry approach, which was followed by a multivariate stepwise selection algorithm based on the minimisation of Wilks' lambda to identify the optimum combination of properties and create the composite fingerprint.

The next stage involved the application of a numerical mixing model to apportion fine sediment sources within the catchment. However, before the model could be applied, the geochemical property concentration data was statistically analysed for particle size correlation using Spearman's rho (Haley, 2010). The correlation was based on the specific surface area (SSA), a surrogate measure of grain size that is readily measured using a Laser Granulometer (see Chapter 3). If there were significant correlations between SSA and property concentrations, a particle size correction factor was integrated into the model to account for any particle size dependencies. A tracer specific weighting factor was also incorporated into the modelling process to reflect the discriminatory power for the source properties. The mixing model used these correction factors and composite fingerprint properties identified in the preceding sediment source discrimination phase to establish the relative sediment contributions from the respective source groups within the catchment. The final stage in this procedure involved an error assessment of the sediment mixing model which was performed using the relative mean error (RME) statistic. It was important to confirm that the associated relative errors did not exceed 15% (Collins *et al.,* 1997c; Walling and Collins, 2000) in order to ensure that the mixing model was capable of providing acceptable predictions of the relative source contributions. If the errors were not considered acceptable, alternative combinations of fingerprint properties through DFA were considered in order to balance sufficient source discrimination with acceptable relative error (Haley, 2010).

5.3 Property Range Test

A fingerprint property range test was utilised to ensure that the suspended sediment samples were represented by the potential source material, thereby confirming whether all potential source types had been included in the catchment sampling process (Collins *et al.,* 2010a). It is recognised that the optimum composite fingerprint must incorporate suspended sediment properties which lie within the range of the corresponding concentrations represented by the source material (Walden *et al.,* 1997). Properties that failed to meet this requirement were consequently excluded from further stages of fingerprinting to ensure accurate sediment source ascription during the modelling phase. However, it is unclear from the existing literature whether this analysis is consistently used within sediment provenance studies. Nevertheless, as this study is concerned with identifying the sources of suspended sediment within the Lugg catchment, there is a possibility that properties could be subjected to enrichment or chemical alteration during the sediment delivery process or during post-depositional processes (Foster *et al.,* 1996; Motha *et al*., 2002; Gordeev *et al.,* 2004). It was therefore deemed necessary to undertake this range test on potential source material and suspended sediment samples independent of any prior analysis.

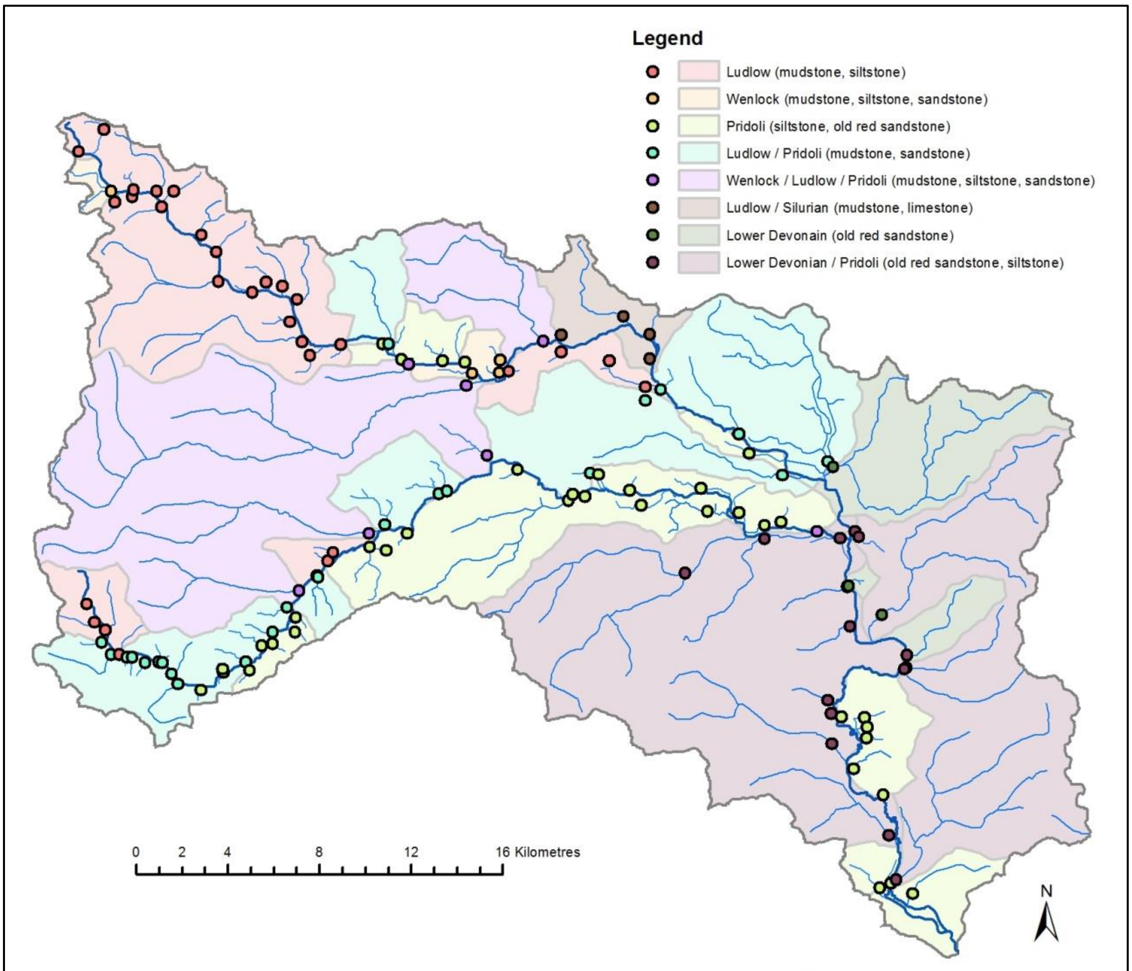
It was also important to undertake this analysis separately for each individual sub-catchment as geochemical property behaviour can be affected by catchment-specific environmental factors, including natural processes, landscape vulnerability and anthropogenic activities. For example, increased weathering and erosion rates could cause the enrichment of particular trace elements that are concentrated in the local lithology and overlying soils (Gordeev *et al*., 2004). Field application of chemical fertilisers, pesticides and herbicides could also cause the enrichment of sediment-bound nutrients through the delivery of fine sediment from agricultural sources, which are likely to vary according to specific catchment land use (Greig *et al*., 2005; Haygarth *et* *al*., 2005; Edwards and Withers, 2008). Furthermore, during transport processes, heavy metal properties could become concentrated in fine sediments through road runoff, especially during heavy rainfall events (Brown and Peake, 2006). This property range analysis could therefore be considered as a test of property behaviour following erosion, transport and post-depositional processes.

The property range test was drawn from Haley (2010), who used conditional formulae to calculate the variation in property concentration ranges between potential source material and suspended sediment. This logical test identified which suspended sediment properties fell within the source concentration ranges and, therefore, which properties failed the analysis. Mean source concentration values and their associated standard deviations were determined for each source group and applied in this analysis. The source range was subsequently defined as values bounded by the standard deviation on the minimum mean property concentration value. The suspended sediment range was defined by the minimum and maximum property concentration values. However, it was important to treat each suspended sediment sample independently to allow greater statistical verification over different flood events. It was, therefore, only those suspended sediment properties which fell completely outside of the corresponding source range that were deemed to fail this particular analysis. Properties which passed this stage were then incorporated in the sediment source discrimination procedure.

5.4 Sediment Source Discrimination

Statistical verification of tracer parameters is a key requirement in using a composite fingerprint approach to discriminate between potential source materials (Minella *et al.,* 2008). It ensures that the source discrimination is accomplished in an unequivocal manner identifying the inclusion of redundant properties in the composite fingerprint (Collins *et al.,* 1998; Collins and Walling 2007a). A two-stage statistical procedure was proposed by Collins *et al.* (1997c) to test the ability of fingerprint properties to discriminate sediment samples, collected to represent individual source types. Subsequently, this procedure has successfully been adopted in several sediment provenance studies (for example, Owens *et al.,* 1999; Russell *et al.,* 2001; Gruszowski *et al*., 2003; Walling 2005; Collins and Walling 2007a; Minella *et al.,* 2008; Walling *et al.,* 2008; Collins *et al.,* 2009; 2010b; 2010c; 2012). This statistical technique was used to identify composite signatures capable of discriminating spatially-derived sediment from individual sub-catchments (during the first phase of analysis), along with specific source types within significant sub-catchments in the study area (throughout the second phase of analysis) (Collins *et al.,* 1997c).

During the first phase of analysis, individual tributaries were characterised as spatial sources by capturing sediment at the outlet of each tributary sub-catchment (as identified in Chapter 3). This characterisation intended to represent the fine sediment delivered from individual sub-catchments. However, owing to the intensive nature of this sampling strategy, the number of potential sediment sources being discriminated exceeded the number of fingerprint properties being considered to form the composite fingerprint. This therefore led to a lack of dimensionality (Collins *et al.,* 2009), which could lead to groups of source samples that are ‘numerical multiples’ of one another (Walden *et al*., 1997). To satisfy dimensionality for this phase, tributary samples were classified according to the dominant geology established in each sub-catchment (for example, Collins *et al.,* 1998; Walling *et al.,* 1999b; Bottrill *et al.,* 2000). Therefore, the number of source samples being discriminated during the statistical verification process were reduced (Figure 5.2). In contrast, source discrimination throughout the second phase of analysis, which focused on individual source types within significant sub-catchments, was considered to satisfy the issue of dimensionality as the number of fingerprint properties exceeded the number of potential source types being discriminated (Collins *et al.,* 2009).



Meridian 2 National [SHAPE geospatial data], Scale 1:50000, Tiles: GB, Updated: July 2012,
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Figure 5.2 The geological classification of tributary sub-catchment source samples.

The two-stage statistical procedure to identify the optimum composite fingerprint properties that was implemented within this study is detailed in the following sub-sections.

5.4.1 Kruskal-Wallis H-Test

The first stage of the statistical verification procedure required a non-parametric test to examine the ability of individual tracer properties to distinguish between specific source types. This evaluated those properties that exhibited significant differences between individual source types. According to Collins *et al.* (1998), sediment fingerprint property data is inconsistently distributed and exhibits unequal variances rendering it incapable of satisfying the conditions for adopting parametric equivalents. Various non-parametric statistical methods have therefore been used within sediment provenance analysis (Davis and Fox, 2009). For example, a number of previous studies have used a Mann-Whitney *U*-test to establish significant differences between two individual source types (Collins *et al.,* 1997c; Carter *et al*., 2003; Gruszowski *et al*., 2003; Porto *et al*., 2005). However, the majority of fingerprinting studies employ a Kruskal-Wallis *H*-test to discriminate between two or more potential source groups (Walling *et al*., 1999b; 2001; Collins and Walling 2007a; Minella *et al*., 2008; Collins *et al.,* 2010b; 2012); as such, this test was adopted herein and applied using SPSS.

Throughout the first phase of analysis the Kruskal-Wallis *H*-test was used to examine the ability of individual fingerprint properties to distinguish between sub-areas of the Lugg catchment associated with different geological characteristics. It was also used during the second phase of analysis to identify which properties were capable of discriminating between sources types based on different land use practices and channel banks in significant sub-catchments. The application of the Kruskal-Wallis *H*-test was appropriate for this study owing to the relatively small source sample sets collected for each sub-catchment and individual source type (Hammond and McCullagh, 1978). It generated test statistics (*H*-values) that were produced using Chi-square values with K-1 degrees of freedom (*df*). The associated critical *H*-values were calculated in accordance with the specific *df* value. Significant inter-group contrasts generate test statistics that exceed the critical value and therefore reject the null hypothesis (H_0), which states that tracer properties exhibit no significant differences between individual source categories (Shaw and Wheeler, 1985; Collins and Walling, 2002). Any significant output, however, is indicative of source inter-group contrasts rather than confirming differences between all possible pairs of source groups, as the test is applied to the values of a specific property for the source material dataset as a whole (Fowler and Cohen, 1990; Collins *et al.,* 2009). Individual tracer properties that failed to demonstrate significant inter-group contrasts, generating *H*-values that did not exceed the critical value were therefore rejected (Collins *et al.,* 2012).

A probability level of 95% was considered suitable (Collins *et al.,* 2010b), with fingerprint properties passing this criteria progressing to stage two of the statistical process.

5.4.2 Discriminant Function Analysis

The second stage of the statistical verification procedure involved the use of multivariate Discriminant Function Analysis (DFA) to test the ability of the tracer properties to classify potential source material into correct categories and to identify the set of tracer properties that afforded optimum discrimination between source groups (Walling *et al.,* 2008). For DFA to be successful it was important that the recommended case-to-variable ratio of 3:1 was not exceeded (Tabachnick and Fidel, 1996). The number of potential sediment source samples was therefore required to outweigh the number of tracer properties considered for the analysis. This criterion was satisfied owing to the nature of the sampling programme, where many representative potential source samples were collected throughout the study area.

DFA was undertaken using SPSS and was originally used to assess the discriminatory power of individual fingerprint properties. It was consequently employed to determine the discrimination of potential catchment sediment sources by using a simultaneous entry approach. This technique, which involved individually entering each fingerprint property into the analysis, was utilised to test the assumption that source discrimination is more powerful when using composite fingerprints compared to individual fingerprint properties (Collins and Walling, 2002). Following this, a multivariate stepwise selection algorithm based on the minimisation of Wilks' lambda was employed to identify the optimum composite fingerprint to provide sufficient discrimination between potential sediment source materials. The Wilks' lambda procedure selects the individual tracer property at each step that minimises the overall lambda statistic. Lower lambda values are therefore associated with composite fingerprints that are capable of providing comprehensive discrimination of the geological sub-areas within the study catchment, and of individual source types within significant sub-catchments (Collins *et al*., 1998).

The stepwise selection procedure aims to maximise the discrimination between the source groups whilst minimising the combination of tracer properties in order to provide the ideal multivariate tracer suite for sediment fingerprinting (Minella *et al.,* 2008; Davis and Fox, 2009). Properties were entered and removed individually in order of their explanatory power and on the basis of partial *F* test statistics. The *F*-to-enter test evaluates the significance of the added discrimination introduced by an individual property, while taking into account the discrimination already achieved by the properties previously entered (Klecka, 1980). If this significance is greater than the default level of 0.05 the property is disregarded as it will not contribute enough to the overall discrimination. The *F*-to-remove test assesses the significance of the decrease in discrimination if that particular property is removed from the previously selected tracer properties (Klecka, 1980). If this significance is greater than the default level of 0.10 the property is removed from the procedure as the discriminatory power of individual properties might decrease owing to correlations with other properties that have subsequently been entered. Properties must also pass a minimum default tolerance level of 0.001 (Collins and Walling, 2002; Collins *et al.,* 2009; 2010b) to ensure redundant properties with small tolerance levels are not selected during the procedure. Individual properties were therefore only selected during the stepwise selection procedure if source discrimination was improved, with the process ceasing once all source material samples were classified correctly or when sample discrimination could not be improved by including any of the remaining tracer properties (Collins and Walling, 2007a).

It was important to utilise both the simultaneous entry and stepwise selection procedures during the study to ensure an acceptable level of discrimination was generated. The stepwise selection procedure usually offers greater discrimination and a more reliable composite fingerprint, as weak or redundant tracer properties are eliminated during the process. In contrast, these properties are included during the simultaneous entry method, which could substantially increase the number of source misclassifications (Klecka, 1980). However, although the stepwise procedure produces an optimal set of discriminating properties it does not guarantee the best combination (McGarigal *et al*., 2000). Since this process enters and removes properties on the basis of individual tracer significance, it does not take into consideration the possibility that individual insignificant properties could become significant and provide greater discrimination when grouped together. As a consequence, it is possible that the simultaneous entry method could yield greater discrimination compared to the stepwise selection algorithm, as found by Haley (2010).

During the DFA potential source material was classified into groups based on geological sub-areas within the catchment (first phase of analysis) and land use types within significant sub-catchments (second phase of analysis). The reliability of the DFA and classification power was assessed by using the leave-one-out cross-validation procedure (Lachenbruch, 1967; Reimann *et al.,* 2008). It successively classifies all cases (i.e. source samples) except one to develop a discriminant function. The case that was originally excluded was then classified, a process which is sequentially repeated with each case left out (Shaw 2003; Burns and Burns 2008). This procedure incorporated the size of the groups into the classification of cases using the discriminant functions in order to test how well the group of tracers selected through the DFA procedure correctly identifies each source sample as belonging to the correct source group. This classification has been utilised in previous sediment fingerprinting studies (e.g. Martínez-Carreras *et al*., 2010a; Zhang *et al*., 2012; Dutton *et al*., 2013; Barthod *et al.,* 2015; Cooper *et al*., 2015; Gorman Sanisaca *et al*., 2017). However, DFA outputs have also been provided by the original classifications, which integrates cases being predicted in the categorisation process. For example, Haley (2010) used original classifications in the DFA outputs as this technique usually generates a superior outcome compared to the cross-validated classification procedure. Nevertheless, the cross-validation technique produces a more reliable presentation of the power of the discriminant function and consequently generates a less biased estimate of classification accuracy. It was therefore necessary that this study utilised this categorisation procedure since discriminant analysis inflates accuracy when the cases classified are the same cases used to determine the discriminant functions (Burns and Burns, 2008).

The resulting statistically-verified composite fingerprint can therefore offer the greatest discrimination between the potential sediment sources. Properties that failed to afford a means of discriminating potential sediment sources were not included in the composite fingerprint as they may contribute to spurious source apportionment (Walling *et al*., 2002a). As a result, only those properties that were able to provide maximum discrimination were used to apportion fine sediment sources within the Lugg catchment.

5.5 Sediment Source Apportionment

The final stage in the sediment fingerprinting procedure involved estimating the relative contributions from the potential source material within the study area to the individual suspended sediment samples. The identified composite fingerprints were used in conjunction with a multivariate numerical mixing model. This provided quantitative information on sediment contributions from individual sources by comparing the specific suspended sediment signatures with those of the potential source material (for example, Walling *et al*., 1993; Collins *et al.,* 1996; 1997c; 1998; 2001; Krause *et al.,* 2003; Wallbrink *et al.,* 2003; Motha *et al*., 2003; 2004; Walling, 2005; Collins and Walling, 2007a; Minella *et al*., 2008; Collins *et al.,* 2010a; 2012; Owens *et al*., 2016; Manjora *et al*., 2017; Zhang *et al*., 2017; Nosrati *et al*., 2018; Tiecher *et al.,* 2018). Sediment mixing models are founded on the assumption that the property concentrations comprising the composite fingerprint for any given suspended sediment sample reflect the corresponding concentrations in the original sources and the relative inputs contributed by those sources (Walling *et al*., 2002a; Collins *et al*., 2009).

Previous sediment provenance studies have utilised sediment mixing models based on linear programming or multiple regression analysis (Yu and Oldfield 1989; 1993; Caitcheon 1993). However, more recent studies have employed mixing models based on optimisation algorithms (Collins *et al*., 1997c; Walling *et al*., 1999b; Owens *et al.,* 1999; 2000; Walling 2005; Collins and Walling 2007a; Collins *et al*., 2010a; 2012), which are a much simpler in that they avoid the need to establish empirical mixing model equations (Walling *et al.,* 1993). This study utilised a mixing model algorithm to identify the sources of fine sediment within the Lugg catchment. The following sub-sections will detail how the model was applied and developed throughout the study.

5.5.1 Application of Mixing Model

A multivariate mixing model, based on previous sediment provenance studies conducted by Owens *et al*. (1999), Walling *et al*. (1999b) and Walling (2005) was originally utilised to estimate the relative contribution of fine sediment being delivered from different sub-catchments to particular suspended sediment samples at key sites within the Lugg catchment (Equation 5.1). Within the model algorithm, a linear equation is constructed for each tracer property in the composite fingerprint to compare the concentration values of each property in a given suspended sediment sample with the corresponding value representing the sum of the predicted contributions from the different source groups (Walling *et al.,* 1999b). However, according to Collins *et al.* (1997c; 2010a), the series of linear equations which represent the composite fingerprint are generally considered to be over-determined as the number of fingerprint properties is usually greater than the number of source groups (Haley, 2010). The set of linear equations could not be solved directly since over-determined linear equations are unable to provide an appropriate solution. Consequently, the least-squares method was used to provide optimised estimates of the relative contributions from each source by minimising the sum of squares of the weighted relative errors (Walling *et al.,* 1999b; Collins and Walling 2007a; Collins *et al.,* 2012) viz.:

$$\sum_{i=1}^{n}\left\{\left(C_i-\left(\sum_{s=1}^{m}S_{si}P_s\right)\right)/C_i\right\}^2 \tag{5.1}$$

where: C_i = concentration value of fingerprint property (i) in the suspended sediment sample; S_{si} = concentration value of fingerprint property (i) in source category (s); P_s =the optimised percentage contribution from source category (s); n = number of fingerprint properties comprising the optimum composite fingerprint; m = number of potential sediment source types.

For the sediment mixing model to be successful in apportioning sources of fine sediment in the catchment, two key linear boundary constraints had to be satisfied during the model iterations. Firstly, the relative contributions from the individual source types (P_s) must lie in the range of 0 to 1 (Equation 5.2) to ensure that equal weight is given to the individual fingerprint properties (Walling, 2005). Secondly, the combined relative contributions from all potential sediment sources must sum to unity (Equation 5.3):

$$0 \leq P_s \leq 1 \tag{5.2}$$

$$\sum_{s=1}^{n} P_s = 1 \tag{5.3}$$

The numerical mixing model was run using the Solver optimisation tool available within Microsoft Excel (Walling and Collins, 2000; Walling *et al.,* 2002a; 2003). The Solver software add-in was developed by Fylstra *et al*., (1998) and works by minimising a target cell (i.e. the sum of squares of the weighted relative errors) through the alteration of the source type proportion values. The improved target cell value and adjustable cells are updated in the spreadsheet, with this process repeated until the target cell output cannot be reduced any further or until the maximum number of iterations have been achieved (Haley, 2010). The final outputs from this procedure are expressed as percentages that represent the relative contributions of each source to the individual suspended sediment samples (Minella *et al.,* 2008).

The mixing model was used to apportion sources of fine sediment from individual sub-catchments based on the source material collected (actively transported fine material on the bed surface, channel bank material and till outcropping located at the base of banks). These relative contributions were then aggregated for each sub-catchment to provide an estimation of the sediment contributed from individual outlets, regardless of source type. This aggregation is perceived to enable the identification of significant sub-catchments within the study area as the fine sediment derived from these outlets can be expected to represent a 'local' mixture of sediment that is actively transported through the system. It was therefore used to inform the locations that warranted an in-depth, meso-scale sediment provenance study.

The individual suspended sediment samples collected from each sink site were associated with a range of both flow conditions and suspended sediment concentrations (Owens *et al*., 2000; Russell *et al.,* 2001). Consequently, it was necessary that the contributions from the source types calculated for each sampling site were weighted according to suspended sediment load at the time of sampling. The magnitude of the sediment load over the duration of each sampling period was taken into account to ensure that greater weight was assigned to source contributions for samples collected during periods of higher sediment loadings (Walling *et al*., 2008). The weighted mean relative contributions of each individual source type to the suspended sediment samples collected at each sink site were therefore calculated (Walling *et al*., 1999b; Owens *et al.,* 2000; Russell *et al.,* 2001; Collins and Walling, 2007a; Minella *et al.,* 2008):

$$P_{sw} = \sum_{s=1}^{n} P_{sx} \left(\frac{L_x}{L_t} \right) \tag{5.4}$$

where: P_{sw} = load-weighted relative contribution from source type (s); P_{sx} = relative contribution from source type (s) to specific suspended sediment sample (x); L_x = the sediment loading during the sampling period represented by suspended sediment sample (x); L_t = the total sediment loading during the period of interest.

This load-weighted approach provided a more realistic estimate of the mean source contributions of suspended sediment samples at each site, over a particular period, than a simple average of the contribution values associated with individual suspended sediment samples (Walling *et al.,* 1999b; Collins and Walling 2007a). This is because individual suspended sediment samples could represent periods of reduced fine sediment storage. The importance of applying this load-weighting procedure was demonstrated in a study by Walling *et al.*

(2008), where the use of the simple mean over-estimated the contributions of various source types whilst under-estimating the contributions of others. This approach was therefore utilised to estimate the mean relative contribution of individual sources to the total suspended sediment load over the entire duration of the sampling period and also over different seasonal periods for each sampling site.

5.5.2 Development of Mixing Model

Since multivariate mixing models were first utilised in sediment provenance studies they have been adapted in the literature to incorporate revised weightings and correction factors (Walling *et al.,* 2003; Collins *et al*., 2009; 2010a; 2012). Particle size and organic correction factors have been incorporated into the model algorithms to take into account the influence of selective delivery and enrichment on sediment geochemistry (Collins *et al.,* 2010c; 2012). It is well known that particle size exerts an important influence on element concentrations in soil and sediment samples (Horowitz and Elrick 1987; Horowitz 1991; Stone and English 1993). Owing to the preferential delivery of finer fractions, suspended sediment samples are typically enriched in fines compared to the corresponding source material (Collins *et al.,* 2009). Consequently, it is essential that a correction factor is utilised to take account of particle size differences between the suspended sediment and source material, as significant grain size composition contrasts prevent direct comparison of their tracer properties (Russell *et al.,* 2001; Minella *et al.,* 2008). Mixing model algorithms have also been developed to include an organic matter correction factor, as it is recognised that organic matter content can have an influence on element concentrations (Hirner *et al.,* 1990).

The revised mixing models have additionally incorporated within-source variability weighting factors to take account of the varying levels of precision associated with individual fingerprint properties (Walling *et al.,* 2002a; 2003; Collins and Walling, 2007a; Collins *et al*., 2012). As the variability of fingerprint property values amplify, the uncertainty associated with source apportionment increases (Small *et al*., 2002; 2004). This weighting factor is therefore incorporated in the algorithm to reflect within-source variation and ensure that the properties providing the greatest precision exert the greatest influence upon the optimised solutions (Collins *et al.,* 1997c; 2010c). As a result, the inclusion of this weighting factor helps to constrain the uncertainty ranges associated with repeat mixing model iterations for source proportions (Collins *et al*., 2010b). Previous studies have also integrated tracer discriminatory weighting factors into the mixing model algorithm to account for specific tracer discriminatory power (for example, Collins *et al.,* 2009; 2010b; 2012). The amalgamation of this weighting factor with the mixing model solutions was required owing to the inevitable discriminatory variation between different tracer properties within the composite fingerprints.

A modified version of the mixing model, based on Collins *et al.* (2010a) and utilised by Haley (2010), was therefore employed to apportion recent fine sediment sources based on specific land-use types within the identified significant tributary sub-catchments. This adapted model works on the same principles and uses a similar approach to the original version in optimising estimates of the relative contributions from the potential sediment sources by minimising the sum of squares of the weighted relative errors (Equation 5.5). However, the revised mixing model algorithm now includes an additional particle size correction factor and tracer discriminatory weighting to provide a more detailed and accurate sediment provenance analysis.

$$\sum_{i=1}^{n}\left\{\left(C_i-\left(\sum_{s=1}^{m}S_{si}P_sZ_s\right)\right)/C_i\right\}^2 W_i \tag{5.5}$$

where: C_i = concentration value of fingerprint property (i) in the suspended sediment sample; S_{si} = concentration value of fingerprint property (i) in source category (s); P_s =the optimised percentage contribution from source category (s); (Z_s) = particle size correction factor for source category (s); (W_i) = tracer discriminatory weighting factor; n = number of fingerprint properties comprising the optimum composite fingerprint; m = number of potential sediment source types.

Within the mixing model, potential sediment sources were represented using the mean concentrations of fingerprint properties within each sediment source category to determine the provenance of individual suspended sediment samples (Collins *et al*., 1998; Walling *et al.,* 2002a; 2008). The suspended sediment samples collected from the sub-catchment outlets represent a mixture of material mobilised and delivered from numerous locations within the catchment area upstream (Walling *et al.,* 2008). Consequently, the collection of representative source samples from a range of locations throughout the individual sub-catchments (as detailed in Chapter 3) is comparable to the natural sediment mixing during sediment mobilisation and delivery processes (Collins *et al*., 2009; 2010b). As a result, the subsequent aggregation of these samples to provide mean fingerprint property concentration values, representative of specific source groups, can be justified.

Particle Size and Organic Matter Correction

It has been established in previous studies that particle size exerts a strong influence on geochemical properties (Gibbs, 1977; Filipek and Owen, 1979; Thorne and Nickless, 1981; Horowitz and Elrick, 1987; Horowitz, 1991; Stone and English, 1993; He and Owens, 1995; He and Walling, 1996; Stamoulis *et al.,* 1996; Foster *et al*., 1998; Queralt *et al.,* 1999). For example, the enrichment of fine sediment particles during sediment transport and delivery processes can have an effect on geochemical concentrations (Ajmone-Marsan *et al*., 2008), as greater trace element concentrations are often associated with finer sediment size fractions (Horowitz, 1991). A particle size correction factor was incorporated within the mixing model algorithm to permit a direct comparison of the fingerprint properties between the suspended sediment and source material samples (Walling *et al*., 2002a; Gruszowski *et al*., 2003). Although confining the sediment fingerprinting analysis to the < 1 mm fraction partly addressed the effects of contrasts in grain size composition (as detailed in Chapter 3), further correction was necessary to take account of the particle size differences within this fraction (Walling *et al.,* 1999b; Chapman *et al*., 2005).

The method used to undertake this correction was based on specific surface area (SSA), which represents a useful surrogate measure of grain size composition. Greater SSA values are associated with decreasing particle size (Walling *et al*., 2000) and can affect the ability of particles to absorb sediment-associated contaminants (Horowitz and Elrick, 1987; Horowitz, 1991). The fingerprint property concentrations of the source material were therefore corrected for differences in grain size composition compared with the suspended sediment samples to ensure comparability between the suspended sediment and source material samples (Gruszowski *et al.,* 2003). This was accomplished by using the ratio of the SSA (m^2 g^{-1}) of each individual suspended sediment sample to the corresponding mean SSA of source material from each source group (Walling *et al*., 1999b; 2002a; Carter *et al.,* 2003; Chapman *et al.,* 2005; Collins and Walling, 2007a; Collins *et al*., 2010a; 2012). An equation described by Owens *et al.* (2000) was utilised to calculate the ratio:

$$C_{si} = C_o \left(\frac{S_{ss}}{S_s} \right) \tag{5.6}$$

where: C_{si} = the particle size-corrected mean concentration of tracer property (i) in source group (s); C_o = the original mean concentration of tracer property i in s; S_{ss} = the specific surface area of the suspended sediment sample (m^2 g^{-1}); S_s = the average specific surface area for each source group (m^2 g^{-1}).

A limited number of past studies have also used SSA to correct for grain size differences but aggregated the individual suspended sediment samples to provide a single mean SSA value. This was then compared with the mean SSA of source material from each source group (Collins *et al*., 1997a; 2009; 2010b). However, as the suspended sediment samples were collected over a wide range of flow events during this study it was important to treat the suspended sediment samples individually, as specific flow events are likely to transport different particle sizes, generating variable SSA values.

Although this correction method did not determine a precise relationship between SSA and element concentrations for each fingerprint property (He and Walling, 1996), it did provide a suitable and effective means of correcting the fingerprint properties for each source group (Russell *et al.,* 2001; Walling *et al.,* 2002a). It assumes that there is a linear relationship between fingerprint property concentration and SSA, while enabling an essential comparison between suspended sediment samples and source material by taking into account particle size selectivity (Collins *et al.,* 2009; 2010b). However, the relationship between SSA and property concentration is regarded as being non-linear (Horowitz, 1991; He and Owens, 1995) and as a consequence Russell *et al*. (2001) have argued that simple linear correction factors will be inappropriate for correcting property concentrations. Nevertheless, according to Chapman *et al.* (2005) the impact of using a linear correction depends on the proportion of a sample containing very fine particles with a high SSA value. Since the SSA of samples collected within this study ranged from 0.92 to 1.51 $m^2 g^{-1}$, the effect of non-linearity in SSA correction was therefore considered to be negligible. Therefore, this correction method was regarded as appropriate.

No corrections were introduced into the mixing model algorithm to account for differences in organic matter between the suspended sediment samples and source material, owing to the difficulty in generalising the complex relationship between geochemical concentrations and organic matter content (Walling *et al.,* 1999b; Owens *et al.,* 2000; Russell *et al.,* 2001; Gruszowski *et al.,* 2003; Collins *et al.,* 2010a). Recent research has highlighted that organic matter correction factors can either bias source predictions (Smith and Blake, 2014) or have a limited impact on the source estimates (Pulley *et al.,* 2015). Furthermore, the simultaneous incorporation of both organic matter and particle size correction factors could also result in overcorrection of the source sample fingerprint property values (Collins *et al.,* 1997c; Walling *et al*., 2003; Collins *et al*., 2017). For example, there is a strong inter-relationship between particle size and organic matter, so the influence of organic matter content will, to a certain extent, be included in the particle size correction (Russell *et al.,* 2001) as the roles of these factors in influencing property concentrations are likely to be closely related (Collins *et al*., 2009). The application of a linear, ratio-based corrected factor based on organic carbon content (Peart and Walling 1986; Collins *et al*., 1997c; 1998; Walling *et al.,* 2002a; 2003) may also over-simplify the relationship between geochemical concentrations and organic matter content (Haley, 2010). An organic matter correction factor was, therefore, not used in the mixing model iterations.

Tracer Discriminatory Weighting

Owing to the variable discriminatory power of individual properties within the composite fingerprint, a tracer discriminatory weighting was incorporated into the mixing model algorithm. Composite fingerprints that include various properties often generate a wide range of individual property discrimination and subsequent mixing models thus require a weighting to account for this variability. In this study, individual weightings were based on the relative discriminatory efficiency of each fingerprint property and were determined by the results of the DFA (Collins *et al*., 2009; 2010b; 2012). By individually introducing each property in any given composite fingerprint into the DFA process percentages were generated for the source samples that were classified correctly. These percentages are then used to calculate the individual weighting factors (Collins *et al*., 2010b; 2012; Haley, 2010):

$$W_i = \left(\frac{d_1}{d_2}\right) \tag{5.7}$$

where: $W_i =$ the property-specific discrimination weighting factor; $d_1 =$ the individual property discrimination percentage; $d_2 =$ the smallest individual property discriminatory weighting within the composite fingerprint.

By including a tracer discriminatory power weighting, the range of source contributions generated by the mixing model iterations are constrained as the discrimination of the source samples collected from any catchment vary for each property in the corresponding composite fingerprint (Collins *et al.,* 2009). The optimised mixing model solutions in this study were weighted on this basis.

5.5.3 Grain Size Correlation

It has been acknowledged that within fluvial environments a positive correlation usually exists between decreasing grain size and increasing geochemical property concentrations (Filipek and Owen, 1979; Horowitz and Elrick, 1987; Horowitz, 1991). However, it has been observed that this relationship is not necessarily linear as high property concentrations can also be associated with coarser particles (Filipek *et al.,* 1981; Tessier *et al*., 1982; Brook and Moore, 1988; Moore *et al.,* 1989; Vaithiyanathan *et al*., 1993; Stone and Droppo, 1996; Singh *et al*., 1999). This variability and the apparent reduced dependency on grain size can be attributed to the geochemical character of the environment that is likely to be site-specific (Horowitz, 1991). The sorption intensity and capacity of geochemical properties by sediment is affected by a number of sediment constituents, including, iron and manganese oxides, organic matter and clay minerals (Wang and Chen, 2000). For example, high chemical concentrations can be found in the coarse fraction of suspended sediments due to the preferential concentration of iron and manganese oxides on the coarse particles (Brook and Moore, 1988; Vaithiyanathan *et al*., 1993). The presence of organic matter as separate particles that tend to be associated with the coarser size fractions (Horowitz and Elrick, 1987) can also influence element concentrations as organic matter has the capacity to concentrate various trace elements (Horowitz, 1991). Furthermore, it has been recognised that higher residence times of the coarser fractions within the channel could be responsible for greater element concentrations in the coarser size fractions (Singh *et al.,* 1999).

Owing to this and the assumption that particle size dependencies are uniformly significant, the application of a grain size correction factor when deriving sediment provenance should not be used unless correlations exist between property concentrations and particle size (Moore *et al.,* 1989). It was therefore necessary to statistically analyse the influence of particle size on geochemical property concentrations to inform the decision of when to apply a particle size correction factor within the mixing model algorithm. Although resource constraints during this study prevented a comprehensive analysis on the relationship between the geochemical properties and particle size for individual sediment samples, the basic relationship between sample SSA and geochemical property concentration values was analysed by using a non-parametric Spearman’s rho test. This particular statistical approach was selected as the SSA and property concentration values were not normally distributed, thereby avoiding assumptions that a linear relationship between particle size and element concentrations exists. In addition, López-Moreno *et al.*

(2008) stated that the outputs of using this approach are not affected by any data outliers. It was undertaken using SPSS software and it generated correlation coefficients for the individual properties. It was important that statistical correlations were investigated for each individual property, as trace element grain size relationships differ between different properties (Horowitz, 1991). A significance level of 0.05 was firstly used to measure the relationship between property concentrations and SSA values. A significance level of 0.01 was then used to identify properties that exhibited greater correlation.

It was important to treat each sub-catchment individually in order to identify whether there was a statistical correlation between geochemical property concentrations and particle size, as the effects of particle size are likely to be site-specific. The statistical analysis originally incorporated the whole suite of available geochemical properties to identify base-line correlation coefficients between sample SSA and property concentrations. However, it was important that the correlation of only the significant elements present within each composite fingerprint (identified through the DFA process) was considered when deciding whether a particle size correction factor was necessary. Insignificant or redundant properties that were not included in the composite fingerprint and consequently not used in the sediment source ascription phase could cause a degree of inaccuracy in the resulting correlations. This was considered before uniformly applying a grain size correction factor, thereby avoiding any over-simplification and subsequent over-correction of the relationship between property concentrations and particle size.

Where the majority of property concentrations demonstrated significant correlation with SSA for the individual sub-catchments a particle size correction factor was considered appropriate for inclusion within the mixing model algorithm. However, if this correlation was insignificant it was assumed that the laboratory processing stage, where all source material and suspended sediment samples were disaggregated and sieved to the < 1 mm fraction, enabled grain size effects to be sufficiently accounted for, without the need for further correction (Haley, 2010). Although this approach has endeavoured to take into consideration the uncertainty surrounding the effects of particle size on element concentrations, future studies might incorporate a deeper analysis of this relationship using a fractionation technique (Ajmone-Marsan *et al.,* 2008).

5.5.4 Mixing Model Error Assessment

The sediment mixing model outputs provided estimates of relative sediment source contributions of the suspended sediment samples collected at the outlets of each sub-catchment over different temporal scales. It was important to calculate the error associated with these results in order to confirm whether the generated relative contributions were accurate (Walling, 2005). An error assessment of the mixing model results was therefore performed using the Relative Mean Error (RME) statistic and associated goodness-of-fit, which has been employed in previous sediment fingerprinting studies (Collins *et al.,* 1997a; 1997c; 1998; Collins and Walling, 2007a; Minella *et al.,* 2008; Walling *et al*., 2008; Collins *et al*., 2009; 2010c). The RME involved comparing the actual fingerprint property concentrations for the suspended sediment samples with the corresponding values predicted by the mixing model based on the percentage contribution estimates from each source category (Walling *et al.,* 1999b; Walling 2005). Relative errors provided by this comparison for each property within the composite fingerprints were averaged for each suspended sediment sample collected at the sub-catchment outlets. These individual mean values were then averaged to provide the overall RME for each sub-catchment within the meso-scale study (Collins *et al*., 1997c; 2010c).

It has been suggested by Collins *et al.* (1997c) and Collins and Walling (2000) that in order for the mixing models to provide an acceptable prediction of the fingerprint property concentrations of a suspended sediment sample relative errors should be <15%. Therefore, the associated goodness-of-fit should be >85% to ensure that the relative contributions of the potential sediment sources estimated by the mixing model are reliable (Walling *et al*., 2008). Nevertheless, Minella *et al.* (2008) reported acceptable levels of prediction associated with RMEs of <17% (with an associated goodness-of-fit of >83%). However, whilst this error assessment confirms that the mixing models are successful at predicting sediment provenance it does not necessarily validate the model outputs (Collins *et al*., 1997b). Mixing model validation therefore requires further information, including that from the extensive monitoring programme that was integrated into the macro-scale stage of this study.

5.6 Summary

This chapter has detailed the statistical procedure and various data processing techniques that were adopted in the sediment fingerprinting phase of this study. Source discrimination approaches, prior property range tests and rigorous selection of properties for the numerical mixing model were described. The development of the mixing model to incorporate additional correction and weighting factors in accordance with the advancement of the fingerprint procedure during this study has also been acknowledged. The uncertainties surrounding the effects of particle size on element concentrations were recognised by adopting statistical correlation tests to identify whether grain size correction factors should be consistently applied within the mixing model algorithms. These effects are likely to be site-specific and as a result the analysis was undertaken for each individual sub-catchment. Furthermore, a mixing model error assessment using RME was adopted to ensure that the modelled relative contributions were accurate at predicting the sources of fine sediment. Sediment provenance results that have been generated as a result of this flexible application of the fingerprinting process are reported in the following three chapters.

CHAPTER 6

FINE SEDIMENT SOURCES AT THE CATCHMENT SCALE

6.1 Introduction

This chapter presents the results and interpretation from the sediment source fingerprinting procedure applied to suspended sediment samples collected from the five monitoring sites in the Lugg catchment. The aim of this procedure was to determine the spatial provenance of fine sediment by identifying specific sub-catchments that persistently deliver sediment to key sites over different temporal events. The field methodology and sediment source fingerprinting technique detailed in Chapters 3 and 5 have been applied to establish any spatial and temporal variations in the main contributors of siltation in the River Lugg catchment.

The sediment source apportionment results are divided into two main sections to identify and interpret the spatial and temporal variations in sediment provenance for the individual monitoring sites. The spatial variation section reports the mean relative source contributions for each monitoring site over the entire period of study, which are weighted according to the instantaneous suspended sediment load at the time of sampling (see Chapter 5, equation 5.4). The following temporal variation section examines the differences in suspended sediment sources during different flow events for each monitoring site. This variation is considered in context of prevailing land use and associated land management activities, catchment size, rainfall characteristics and Stakeholder observations of the Lugg catchment.

Owing to the difficultly in knowing where to target fine sediment mitigation resources effectively and efficiently, the Stakeholder Advisory Group required information on fine sediment sources at the catchment scale. The load-weighted mean and temporal variations in relative sediment contributions from individual sub-catchments for each monitoring site were therefore inputted into a GIS framework to identify sub-catchments that were repeatedly contributing to the fine sediment load at each monitoring site. These variations are presented as a series of sub-catchment chloropleth maps to identify fluctuations in source areas. A pilot sediment sourcing strategy was implemented at the beginning of this study (July-December 2010) to test whether the fingerprinting method, using geochemical parameters, would enable relative source contribution differences to be presented and to determine whether the identified differences made environmental sense. The outputs were placed in context of local knowledge of sub-catchments with high fine sediment yield from the Stakeholder group, and supplementary ‘ground truthing’ was undertaken to validate the mixing model results.

6.2 Spatial Variation

The mixing model was used to apportion the relative contribution of fine sediment from individual spatial sources to the suspended sediment samples collected at each monitoring site. These spatial sources comprised the main tributary sub-catchments making up the drainage basin of each site. The key objective of this section was to evaluate the spatial variations in fine sediment contributions at each site and to identify persistent contributors of sediment within the Lugg catchment.

6.2.1 Site 1: Hunton Bridge

At the Hunton Bridge monitoring site, nine main sub-catchment sources were identified, which provided 87% of the suspended sediment material sampled between April 2009 and October 2012. This site represents fine sediment mobilisation and delivery and the total suspended sediment flux in the upper part of the River Arrow catchment. The mixing model suggested that the largest contributors of fine sediment were derived from the Headbrook (13±3%), Glasnant (12±6%), Milton Mill (12±2%) and Newchurch (11±3%) sub-catchments (Figure 6.1). These sub-catchments were respectively situated 4.1, 13.5, 19.1 and 16.4 km upstream of the monitoring site. A further 9±1 and 9±2% of material was identified from the Gilwern Brook and Huntington sub-catchments, situated 3.6 and 9.1 km upstream. Fine sediment derived from Rushock, Sychcwm and Cwmila Brook contribute 8±2, 6±1 and 6±4% of the total suspended sediment respectively. The remaining 13% of the suspended sediment material collected at the Hunton monitoring site comprised seven additional sub-catchments with contributions less than 5% and ranging from 4±1% for the Dan-yr-allt sub-catchment to 1±1% for the Hergest Mill sub-catchment.

A chloropleth map illustrates the load-weighted mean relative contribution from each tributary sub-catchment to the suspended sediment samples collected at the Hunton Bridge monitoring site (Figure 6.2). The greatest contributions are derived from mid-catchment sources, representing 41% of the total suspended sediment. Contributions from headwater sources represent 26% of the total suspended sediment collected at the monitoring site, dominated largely by the Glasnant sub-catchment (12%), whereas relative sediment inputs from the lower parts of the Hunton drainage basin provided 33% of the total suspended sediment.

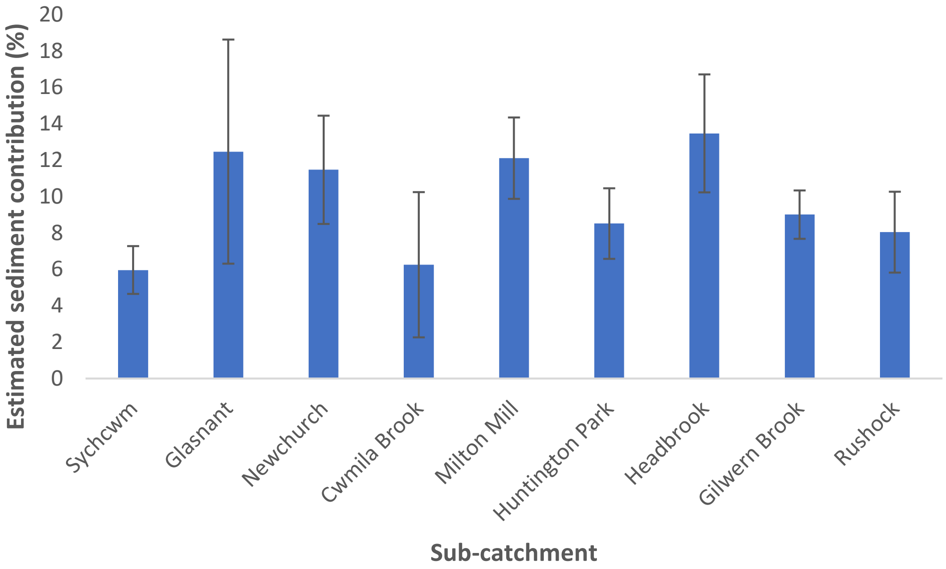

Figure 6.1 Load-weighted mean relative sediment contribution and associated standard errors from most dominant sub-catchments at the Hunton Bridge monitoring site.

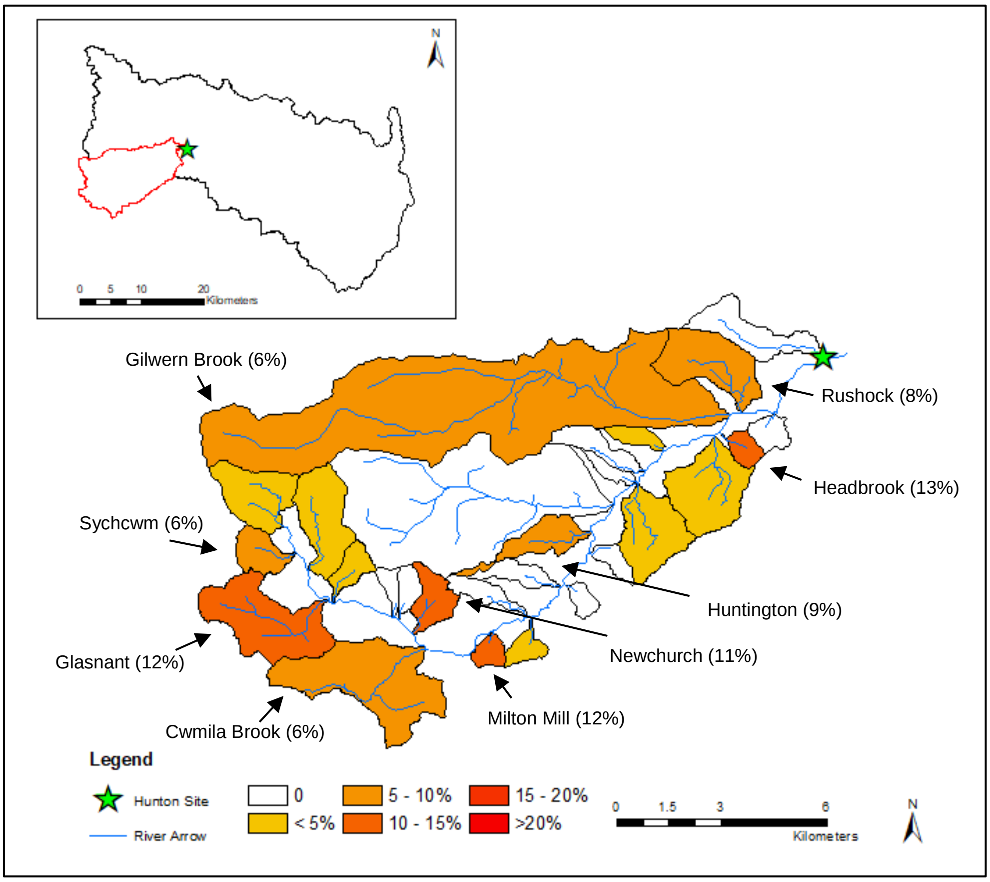

Figure 6.2 Load-weighted mean contribution from each tributary sub-catchment for the Hunton Bridge monitoring site (April 2009 – October 2012).

6.2.2 Site 2: Broadward Farm

Seven dominant sub-catchment sources were identified at the Broadward Farm monitoring site, which contributed 81% of the total suspended sediment sampled between April 2009 and October 2012. This site is located close to the River Arrow catchment outlet and therefore is representative of the total Arrow suspended sediment flux. The mixing model suggested that the largest single contributors of fine sediment were derived from the Honeylake Brook sub-catchment (19±4%), situated 0.2 km upstream of the sampling site and the Curl Brook (15±3%) tributary, situated 12.9 km upstream (Figure 6.3). The Stretford Brook sub-catchment, situated 3.2 km upstream from the monitoring site, was also identified as a large contributor to the total suspended sediment (12±3%). A further 9±2, 9±3 and 9±3% of material was identified from the Moor Brook, Staunton on Arrow and Glasnant sub-catchments, located 4.4, 17.7 and 40.3 km upstream. An un-named tributary at Ivington Common, 2.1 km upstream from the monitoring site contributed 8±3% of the total suspended sediment. The remaining 19% of the suspended sediment material collected at the Broadward monitoring site comprised nine additional sub-catchments with contributions less than 5% and ranging from 4±2% for the un-named tributary at Titley to 1±1% for the Milton Mill sub-catchment.

The load-weighted mean relative contribution from each tributary sub-catchment to the suspended sediment samples collected at the Broadward Farm monitoring site is illustrated by a chloropleth map (Figure 6.4). The greatest contributions are derived from the lower parts of the Arrow catchment, representing 55% of the total suspended sediment and dominated by four of the most dominant sources. Relative fine sediment inputs from the upper Arrow catchment provided 9% of the total suspended sediment, dominated entirely by the Glasnant sub-catchment. This sub-catchment is situated 40.3 km upstream of the monitoring site, suggesting that sediment supply from this source is an important part of the fine sediment flux in the River Arrow catchment. Contributions from mid-catchment sources represent 36% of the total suspended sediment collected at the monitoring site, dominated largely by the Curl Brook tributary (15%).

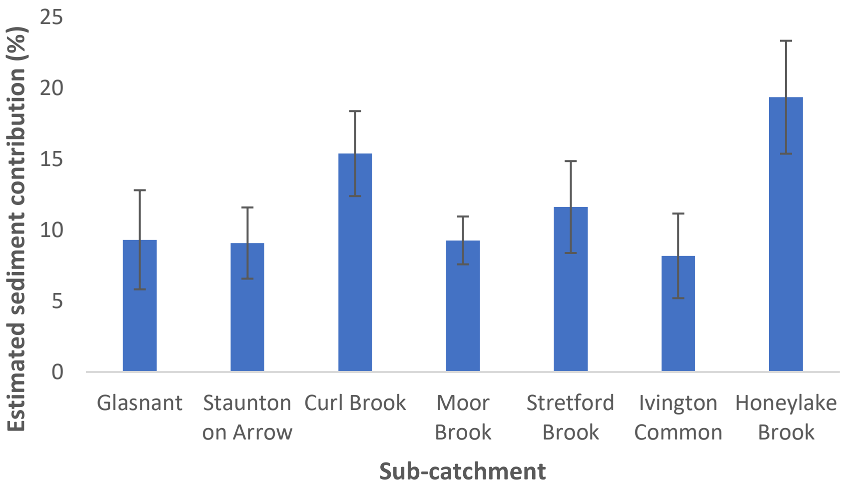

Figure 6.3 Load-weighted mean relative sediment contribution and associated standard errors from most dominant sub-catchments at the Broadward Farm monitoring site.

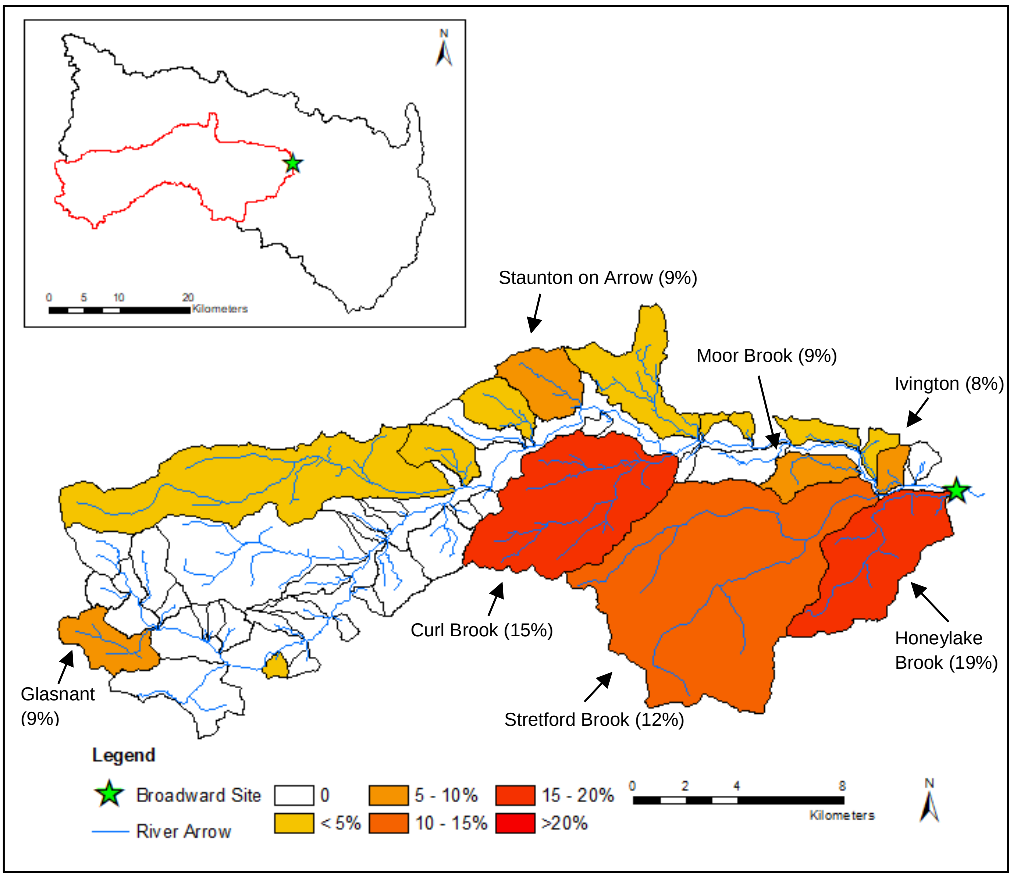

Figure 6.4 Load-weighted mean contribution from each tributary sub-catchment for the Broadward Farm monitoring site (April 2009 – October 2012).

6.2.3 Site 3: Eaton Hall Farm

At the Eaton Hall Farm monitoring site, seven dominant sub-catchments were identified contributing 77% of the total suspended sediment sampled between August 2009 and October 2012. This site represents fine sediment mobilisation and delivery and the total suspended sediment flux in the River Lugg catchment upstream of the River Arrow confluence. The mixing model indicated that the largest single contributors of fine sediment were derived from the Cheaton Brook (23±4%) and Ridgemoor Brook (16±6%) sub-catchments (Figure 6.5). These sub-catchments were located close to the monitoring site (2 and 2.2 km respectively). An un-named tributary at Lucton, situated 11.6 km upstream from the monitoring site was also identified as a large contributor, with an estimated sediment contribution of 13±3%. A further 7±1% of material was identified from an un-named tributary at Treburvaugh, located in the upper part of the Lugg catchment 39.8 km upstream from the sampling site. Fine sediment derived from Cwm Byr and un-named tributaries at Pilleth and Eyton each contribute

6±2% of the total suspended sediment. The latter of these sub-catchment sources is situated in the lower part of the Eaton drainage basin, 6.8 km upstream of the sampling site, whereas the other two are located in the upper parts of the catchment. The remaining 23% of the suspended sediment material collected at the Eaton monitoring site comprised 12 additional sub-catchments with contributions less than 5% and ranging from 5±3% for the un-named tributary at Llangunllo to 1±0% for the Pinsley Brook sub-catchment.

A chloropleth map illustrates the load-weighted mean relative contribution from each tributary sub-catchment to the suspended sediment samples collected at the Eaton Hall Farm monitoring site (Figure 6.6). Like the Broadward monitoring site, the greatest contributions are derived from the lower parts of the Eaton drainage basin, representing 59% of the total suspended sediment and dominated by four of the most dominant sources. Relative sediment inputs from headwater sources provided 23% of the total suspended sediment collected at the monitoring site, dominated largely by the Cwm Byr and Treburvaugh sub-catchments, whereas contributions from mid-catchment sources represent 18% of the total suspended sediment.

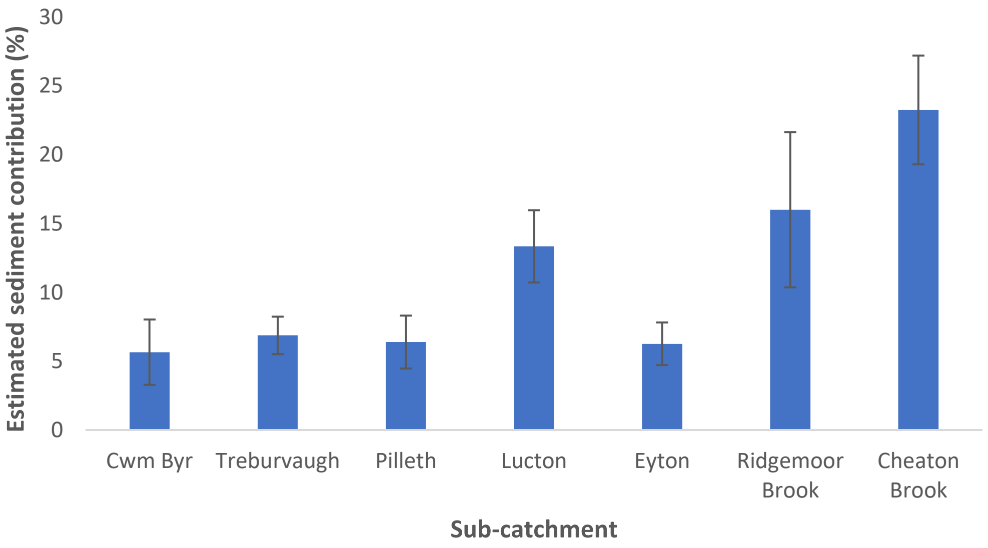

Figure 6.5 Load-weighted mean relative sediment contribution and associated standard errors from most dominant sub-catchments at the Eaton Hall Farm monitoring site.

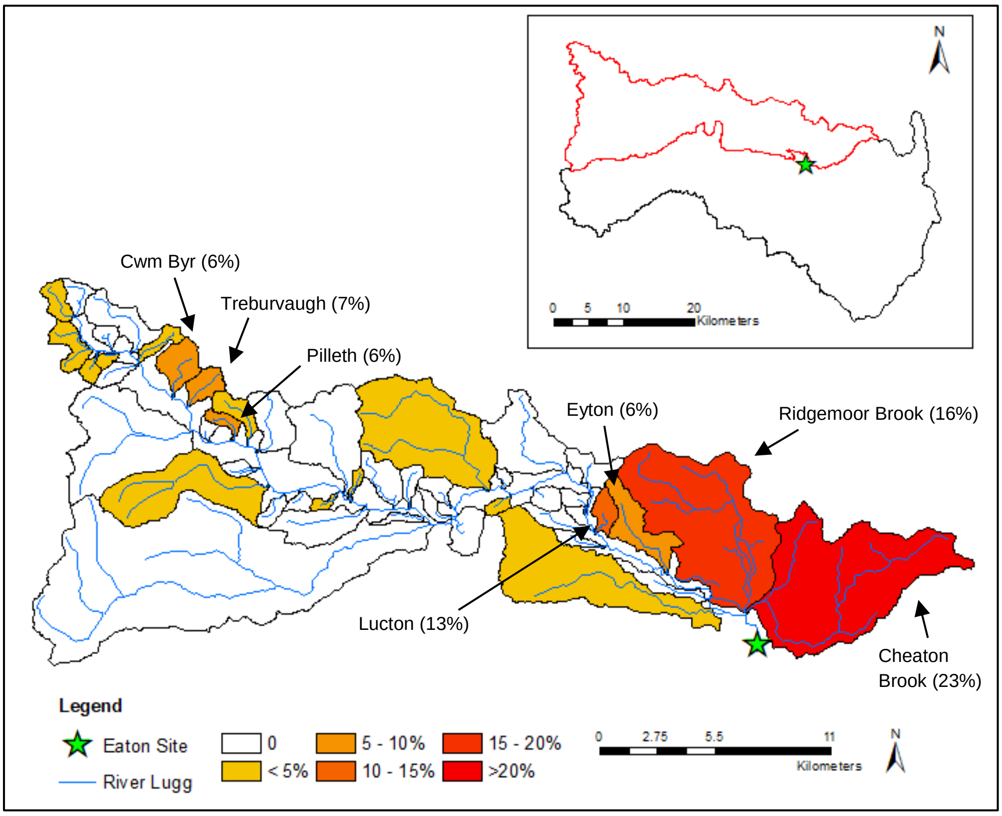

Figure 6.6 Load-weighted mean contribution from each tributary sub-catchment for the Eaton Hall Farm monitoring site (August 2009 – October 2012).

6.2.4 Site 4: Marlbrook Farm

Nine main sub-catchment sources were identified at the Marlbrook Farm monitoring site, which contributed 71% of the total suspended sediment sampled between September 2009 and October 2012. This site represents fine sediment mobilisation and delivery and the total suspended sediment flux in the River Lugg catchment downstream of the River Arrow confluence. The mixing model suggested that the largest single contributors of fine sediment were derived from the Curl Brook (10±3%), Cheaton Brook (10±4%) and Moor Brook (9±2%) sub-catchments, respectively situated 17.3, 6.1 and 8.5 km upstream of the monitoring site (Figure 6.7). The Ridgemoor Brook, Stretford Brook and Glasnant sub-catchments were also identified as large contributors to the total suspended sediment collected at this monitoring site. These tributary sub-catchments were situated 6.3, 7.3 and 45.1 km upstream and were associated with estimated relative sediment contributions of 8±2, 8±3 and 8±5% respectively. A further 7±2 and 6±1% of material was identified from an un-named tributary at Lucton and the Honeylake Brook sub-catchment, situated

15.6 and 4.2 km upstream from the monitoring site. Fine sediment derived from an un-named tributary at Treburvaugh, located in the upper part of the Lugg catchment 42.9 km upstream from the sampling site, contribute 5±1% of the total suspended sediment. The remaining 29% of the suspended sediment material collected at the Marlbrook monitoring site comprised 20 additional sub-catchments with contributions less than 5% and ranging from 3±1% for the un-named tributary at Titley to 1±1% for the Brierley Cut tributary draining from the 'Arrow Fisheries'.

The load-weighted mean relative contribution from each tributary sub-catchment to the suspended sediment samples collected at the Marlbrook Farm monitoring site is illustrated by a chloropleth map (Figure 6.8). Like the Broadward and Eaton monitoring sites, the greatest contributions are derived from the lower parts of the Marlbrook drainage basin, representing 47% of the total suspended sediment and dominated by five of the most dominant sources. Relative fine sediment inputs from mid-catchment sources represent 26% of the total suspended sediment collected at the monitoring site, dominated largely by the Curl Brook tributary (10%), whereas contributions from the upper parts of the catchment provided 27% of the total suspended sediment collected at the monitoring site.

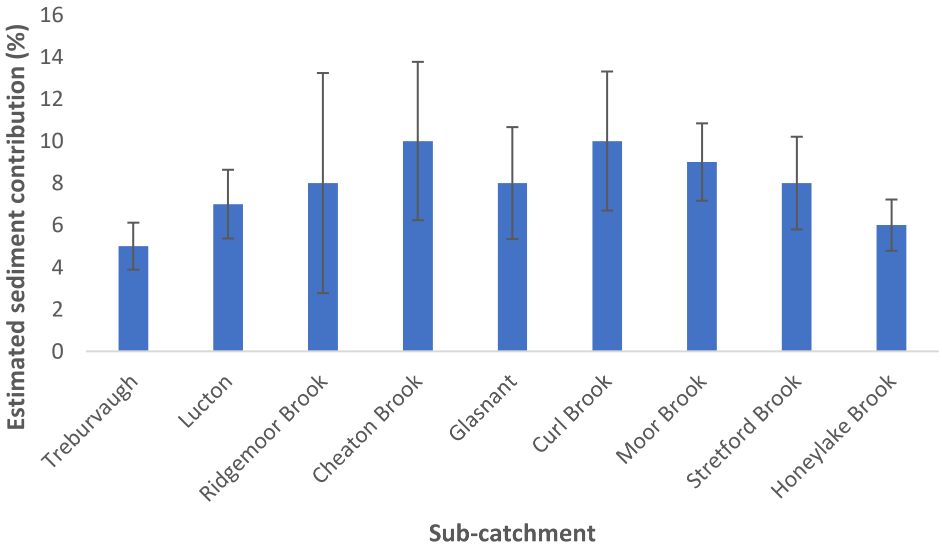

Figure 6.7 Load-weighted mean relative sediment contribution and associated standard errors from most dominant sub-catchments at the Marlbrook Farm monitoring site.

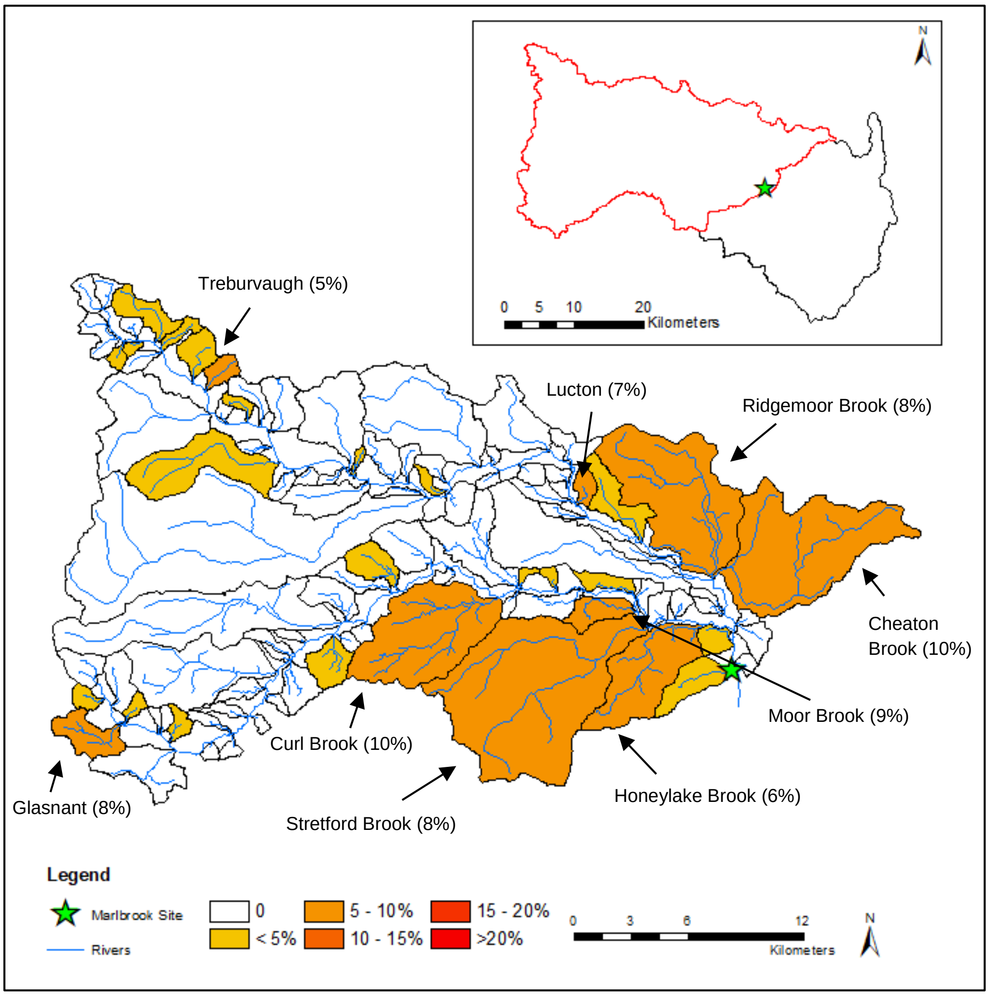

Figure 6.8 Load-weighted mean contribution from each tributary sub-catchment for the Marlbrook Farm monitoring site (September 2009 – October 2012).

6.2.5 Site 5: Lugwardine

At the Lugwardine monitoring site, nine main sub-catchments were identified contributing 64% of the total suspended sediment sampled between August 2009 and October 2012. This site is located close to the River Lugg catchment outlet and therefore is representative of the total Lugg suspended sediment flux upstream of the River Frome confluence. The mixing model indicated that the largest contributors of fine sediment were derived from the Little Lugg (11±2%) and Cheaton Brook (10±2%) sub-catchments (Figure 6.9). These sub-catchments were respectively situated 2.7 and 32.1 km upstream of the monitoring site. The Curl and Stretford Brook sub-catchments were also identified as large contributors to the total suspended sediment collected at this monitoring site. These tributary sub-catchments were situated 43.4 and 33.4 km upstream and were associated with estimated relative sediment contributions of

8±2 and 7±3% respectively. An un-named tributary at Lucton, situated 41.7 km upstream from the monitoring site was also identified as a large contributor, with an estimated sediment contribution of 7±1%. Fine sediment derived from the Glasnant sub-catchment and an un-named tributary at Treburvaugh, located in the upper parts of the Lugg catchment contribute 6±3 and 5±1% of the total suspended sediment respectively. These sub-catchments are situated 71.2 and 69.1 km upstream of the monitoring site, suggesting that sediment supply from these sources are an important part of the fine sediment flux in the River Lugg catchment. A further 5±2% of material was identified from each of the Moor and Ridgemoor Brook sub-catchments, located 34.6 and 32.3 km upstream. The remaining 36% of the suspended sediment material collected at the Lugwardine monitoring site comprised 21 additional sub-catchments with contributions less than 5% and ranging from 4±3% for the Wellington Brook sub-catchment to 1±1% for the Marl Brook sub-catchment.

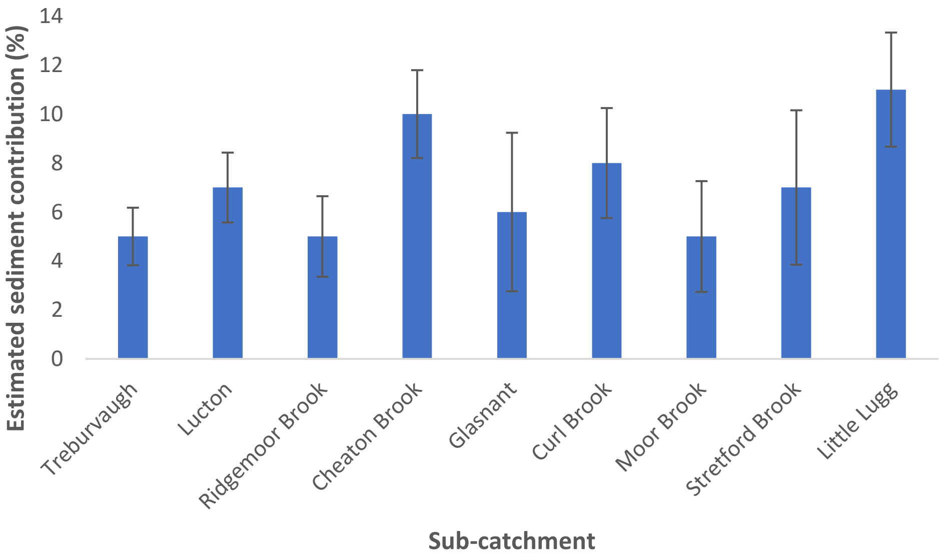

Figure 6.9 Load-weighted mean relative sediment contribution and associated standard errors from most dominant sub-catchments at the Lugwardine monitoring site.

A chloropleth map illustrates the load-weighted mean relative contribution from each tributary sub-catchment to the suspended sediment samples collected at the Lugwardine monitoring site (Figure 6.10). Unlike the other monitoring sites, the greatest contributions are derived from mid-catchment sources, representing 52% of the total suspended sediment and dominated by six of the most dominant sources. Relative fine sediment inputs from the upper and lower parts of the Lugg catchment each provided 24% of the total suspended sediment collected at the monitoring site, with the latter dominated largely by the Little Lugg tributary (11%).

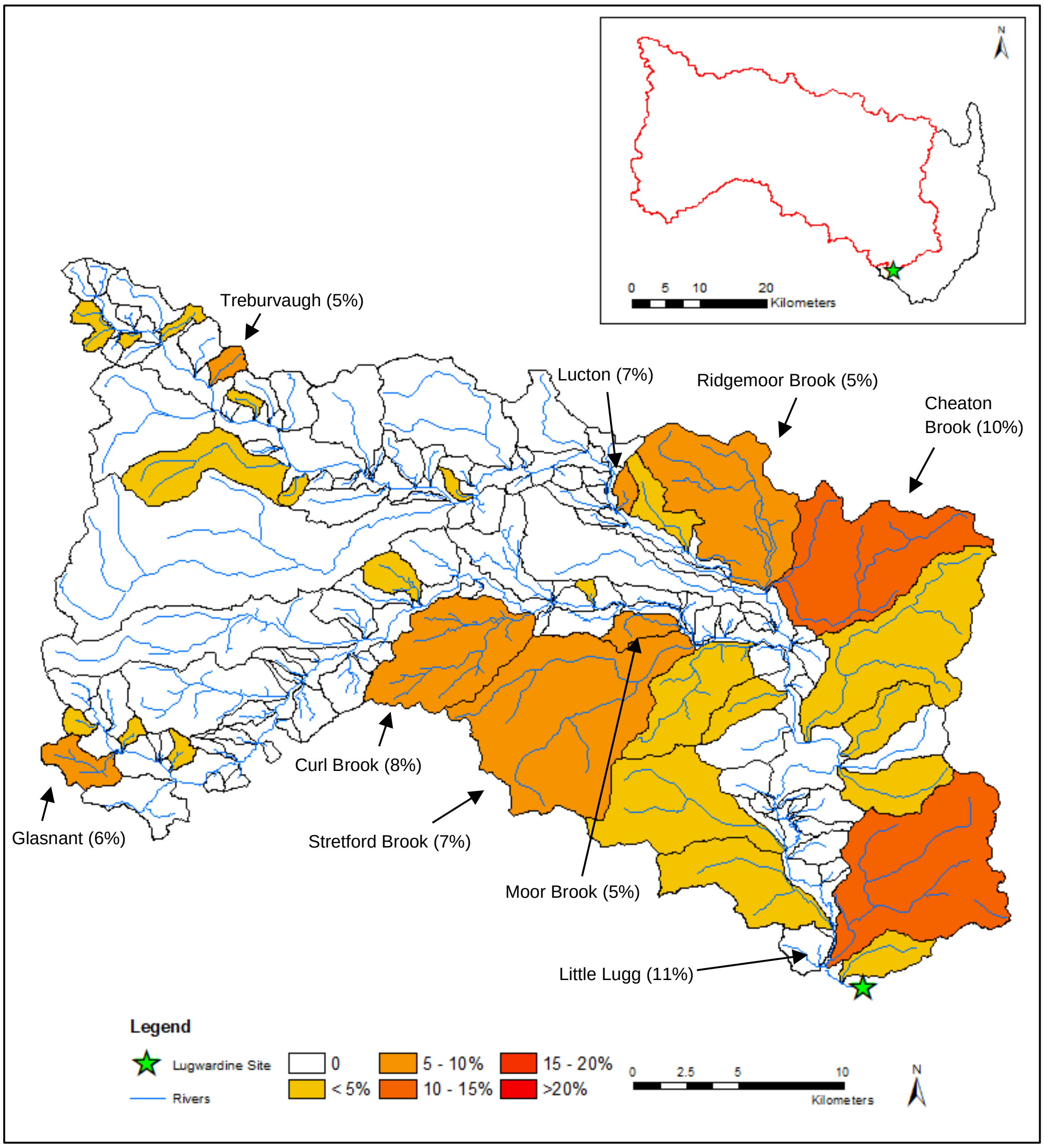

Figure 6.10 Load-weighted mean contribution from each tributary sub-catchment for the Lugwardine monitoring site (August 2009 – October 2012).

6.2.6 Summary

The spatial variations in the relative load weighted mean fine sediment contributions at each monitoring site have identified several tributary sub-catchments that persistently deliver sediment to sink sites within the Lugg catchment (Table 6.1). Most of these sources are situated in the River Arrow catchment, which has been identified by the Stakeholder Advisory Group as being particularly problematic in terms of high suspended sediment loads. Sub-catchments in the Arrow that contribute the greatest proportion of fine sediment to monitoring sites in the Lugg catchment include Glasnant (6-12%), Curl (8-15%), Moor (5-9%), Stretford (7-12%) and Honeylake Brooks (1-19%). Tributary sub-catchments draining into the River Lugg and contributing a high proportion of fine sediment to the monitoring sites include un-named tributaries at Treburvaugh (5-7%) and Lucton (7-13%) and the Ridgemoor (5-16%) and Cheaton Brooks (10-23%). However, in order to fully assess variations in fine sediment contributions and to identify the persistency of individual tributary sub-catchments it is necessary to investigate temporal fluctuations in relative sediment contributions from source areas, which are considered in the next sub-section.

Table 6.1 Estimated sediment contributions of the most persistent sources of fine sediment at each monitoring site.

Tributary sub-catchment	Estimated sediment contributions (%)				
	Site 1: Hunton	Site 2: Broadward	Site 3: Eaton	Site 4: Marlbrook	Site 5: Lugwardine
Glasnant	12±6	9±3		8±3	6±3
Curl Brook		15±3		10±3	8±2
Moor Brook		9±2		9±2	5±2
Stretford Brook		12±3		8±2	7±3
Honeylake Brook		19±4		6±1	1±1
Treburvaugh			7±1	5±1	5±1
Lucton			13±3	7±2	7±1
Ridgemoor Brook			16±6	8±5	5±2
Cheaton Brook			23±4	10±4	10±2

6.3 Temporal Variations

The load weighted mean relative sediment contributions from individual spatial sources reported in the previous sub-section are likely to conceal considerable inter-storm and seasonal variability in the contribution of the individual source groups (Walling *et al*., 1999b). When determining sediment sources for individual flow events it is assumed that the fluvial sediment is representative of what is eroded and transported during that particular event. However, as sediment can be temporarily deposited and stored in the channel, the source ascription may not truly represent the sediment eroded and delivered during that event (Mukundan *et al.,* 2012). Therefore, taking a load-weighted average of the fingerprinting result over a period of time may provide a more meaningful result. This, along with the possibility that the provenance of fine-grained suspended sediment could vary seasonally in response to the seasonal pattern of land use practices and the overall hydrological regimes of the monitoring sites (Jones *et al.,* 2016), suggested that it was necessary to assess seasonal variations in the relative contributions. Flow events sampled at each monitoring site were therefore grouped into climatic seasons as defined in the literature. Winter is represented by the period October – March and summer by April – September. The relative contributions from each sub-catchment, calculated for the sediment samples collected within each season, were then load weighted to provide an average seasonal contribution for each sub-catchment for each monitoring site. The key objective of this section was to establish temporal variations in fine sediment contributions at each site.

6.3.1 Site 1: Hunton Bridge

Temporal contrasts in fine sediment contributions from individual tributary sub-catchments to the Hunton Bridge monitoring site are presented in Appendix 2.1. It is evident that sediment contributions from individual tributary sub-catchments vary significantly over different flow events, with sediment contributions from the Glasnant sub-catchment exhibiting the greatest temporal variation. Sediment contributions from this sub-catchment ranged from as little as zero, or so low that it was not recognised by the mixing model, to a peak of 86% during the 29/04/09-23/07/09 sampling period. Furthermore, this sub-catchment represented the dominant source of fine sediment in five of the first eight events, with contributions ranging from 33% during the 09/09/10-25/10/10 sampling period to 86% during the 29/04/09-23/07/09 sampling period.

Figure 6.11 shows seasonal contrasts in the load-weighted relative contributions from the most dominant tributary sub-catchments to the suspended sediment flux at the Hunton Bridge monitoring site. Contributions from five of the main sub-catchment sources are greatest during the summer season, with the greatest contribution and seasonal contrast identified from the Newchurch sub-catchment (20±5 vs 7±3%). The greatest summer contribution was 45% for the 31/05/10-09/09/10 sampling period, whereas the greatest contribution during the winter season was 28% for the 09/02/12-09/03/12 sampling period. Similarly, a pronounced seasonal contrast is evident for an un-named tributary at Rushock, with a higher relative load-weighted contribution during the summer season (12±4 vs 6±2%). However, it is evident that this is largely driven by a high contribution during the 09/08/12-25/10/12 sampling period (47%), with other contributions during this season ranging between 5 and 9% (Appendix 2.1).

In contrast, contributions from four of the main sub-catchment sources are greatest during the winter season (Figure 6.11), with the greatest contribution identified in the Headbrook sub-catchment (16±6%). Winter contributions were generally greater than 14% with the greatest contribution being 59% for the 28/09/11-08/11/11 sampling period, whereas the greatest contribution during the summer season was 29% for the 24/06/11-17/08/11 sampling period (Appendix 2.1). A seasonal contrast was also evident for the Gilwern Brook sub-catchment, with a higher relative load-weighted average contribution during the winter season (11±2 vs 5±1%). The greatest winter contribution was 23% for the 08/11/11-21/12/11 sampling period, whereas the highest contribution during the summer season was 13% for the 28/06/12-09/08/12 sampling period. Similarly, the Cwmila Brook sub-catchment displays a pronounced seasonal variation in fine sediment contribution to the Hunton monitoring site, with a greater contribution associated with the winter season (Figure 6.11). Fine sediment contributions were estimated to be 10±9% during the winter season and less than 1% in the summer months. However, this distinct contrast is driven by only two individual sampling events between September 2009 and April 2010 with contributions more than 50% (Appendix 2.1), leading to the relatively high standard error associated with this estimated sediment contribution.

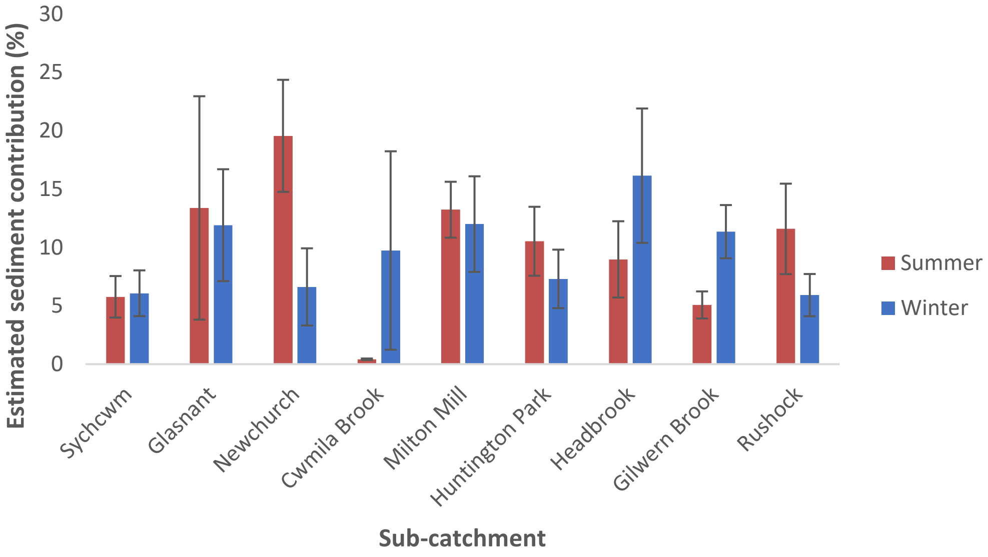

Figure 6.11 Seasonal contrasts in relative sediment contributions and associated standard errors from tributary sub-catchments at the Hunton Bridge monitoring site.

Figure 6.12 illustrates the seasonal contrasts in the load-weighted mean relative contributions from each tributary sub-catchment. Overall, the greatest contributions for both the summer and winter period are derived from mid-catchment sources. However, mid-catchment sediment contributions for the summer period are greater than the corresponding contributions for the winter period (46 vs 39%). This is dominated by the high seasonal contrast evident for the Newchurch sub-catchment, which provides greater summer contributions to the total suspended sediment collected at this monitoring site. Contributions derived from headwater sources are similar for both the summer and winter periods and represent 26 and 24% of the total suspended sediment respectively, whereas contributions from the lower parts of the drainage basin are greater in the winter season (37 vs 28%). This is largely dominated by the seasonal contrasts seen in the relative contributions from the Headbrook sub-catchment, providing greater winter contributions.

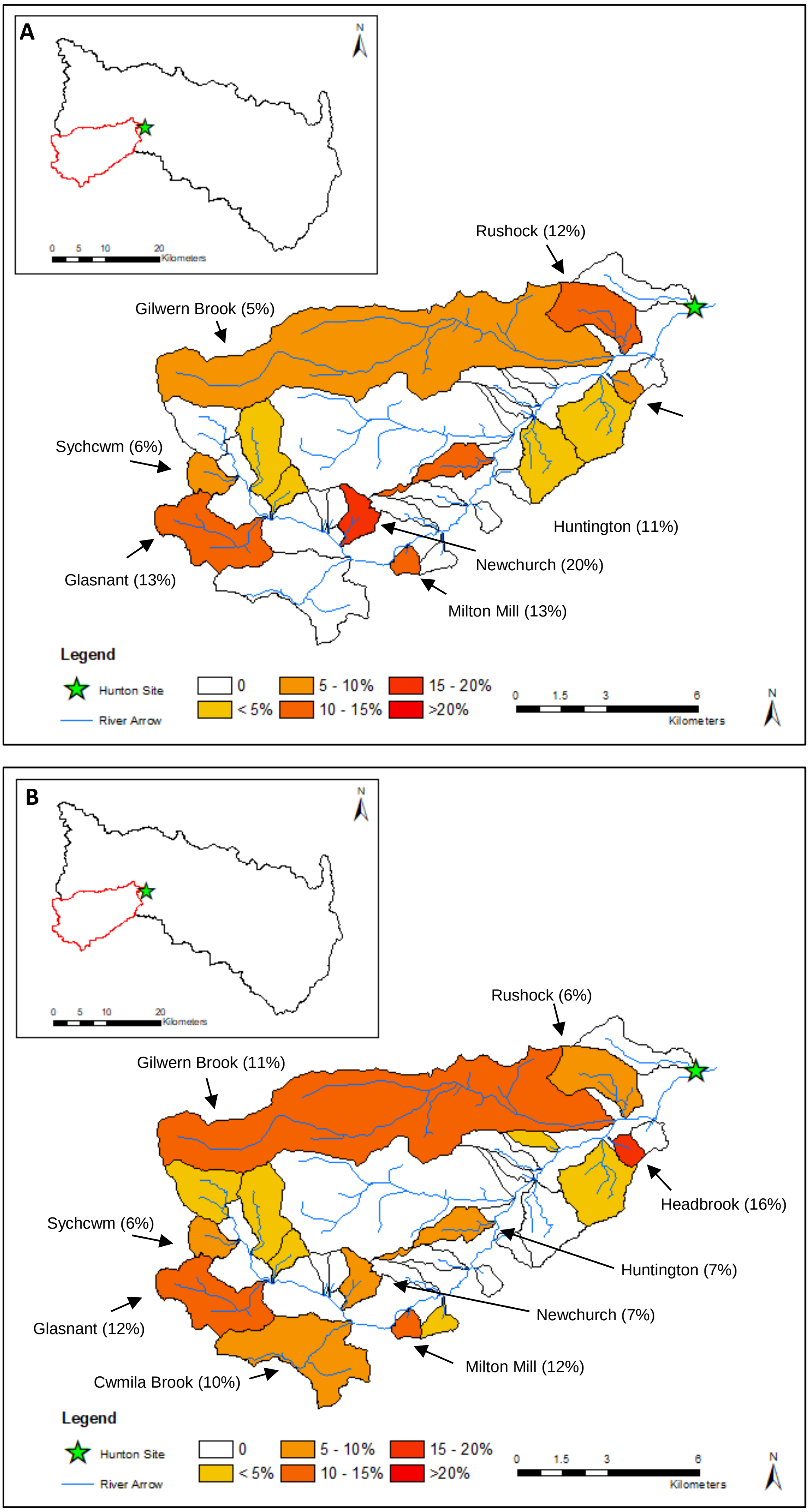

Figure 6.12 Seasonal contrasts in the load-weighted mean relative contributions from each tributary sub-catchment for the Hunton Bridge monitoring site in A) summer and B) winter.

6.3.2 Site 2: Broadward Farm

The temporal contrasts in fine sediment contributions from individual tributary sub-catchments to the Broadward Farm monitoring site are detailed in Appendix 2.2. Sediment contributions from individual sub-catchments vary significantly over different sampling events, with sediment contributions from an un-named tributary at Ivington and the Honeylake Brook sub-catchment showing the greatest temporal variation. Sediment contributions from these sub-catchments ranged from as little as zero to a peak of 53% during the 22/05/12-09/08/12 sampling period at Ivington, and 51% for the 14/06/11-17/08/11 sampling event in the Honeylake Brook. The latter sub-catchment represented the dominant source of fine sediment in nine of the 11 events between September 2010 and February 2012, with contributions ranging from 27% during the 06/12/10-31/01/11 sampling period to 51% during the 24/06/11-17/08/11 sampling period. In contrast, the un-named tributary at Ivington represented the dominant source of fine sediment in two of the last three events, with contributions greater than 25%.

Seasonal contrasts in the load-weighted relative contributions from the most dominant tributary sub-catchments to the suspended sediment flux at the Broadward Farm monitoring site are illustrated in Figure 6.13. Like the seasonal contrasts identified at the Hunton monitoring site, contributions from five of the main sub-catchment sources are greatest during the summer season with the greatest contribution identified from the Stretford Brook sub-catchment (21±5%). The highest contribution during the summer season was 40% for the 31/05/10-07/09/10 sampling period, whereas the highest winter contribution was 32% for the 21/10/10-06/12/10 sampling period (Appendix 2.2). Although the difference between the maximum contributions from each season is not substantial, the 2009 and 2010 summer months were entirely characterised by contributions greater than 30%, whereas only one winter event was associated with contributions greater than this. The greatest seasonal contrast with a higher summer contribution was identified from the Glasnant sub-catchment (20±6 vs 5±3%). This is mainly driven by contributions greater than 35% for the 2009 and 2010 summer periods, with a maximum relative contribution of 41% for the 23/07/09-09/09/09 sampling period. Winter contributions rarely exceeded

20% with a maximum contribution of 25% for the 21/10/10-06/12/10 sampling period (Appendix 2.2).

In contrast, contributions from four of the main sub-catchment sources are greatest during the winter season (Figure 6.13), with the greatest contribution identified in the Honeylake Brook sub-catchment (22±5%). Most events during the 2011 and 2012 winter periods were characterised by contributions greater than 25%, with a maximum contribution of 40% for the 28/09/11-08/11/11 sampling period. Although the load weighted relative contribution of fine sediment was greatest during the winter season, the summer period was associated with a greater maximum contribution (51%) and contributions of more than 40% for the 2011 summer period. However, other summer contributions rarely exceeded 10% with a maximum contribution of 17% for the 31/05/10-07/09/10 sampling period (Appendix 2.2). A pronounced seasonal contrast is also evident for an un-named tributary at Staunton on Arrow, with a greater contribution associated with the winter season (Figure 6.13). Fine sediment contributions were estimated to be 13±5% during the winter season and less than 1% in the summer months. This is mainly driven by a high contribution during the 08/11/11-30/12/11 sampling period (48%), with other contributions during this season not exceeding 15%. A seasonal contrast was also evident for the Moor Brook sub-catchment, with a higher relative load-weighted average contribution during the winter season (11±3 vs 5±2%). The greatest winter contribution was 22% for the 31/01/11-09/03/11 sampling period, whereas the highest contribution during the summer season was 16% for the 17/08/11-28/09/11 sampling period (Appendix 2.2).

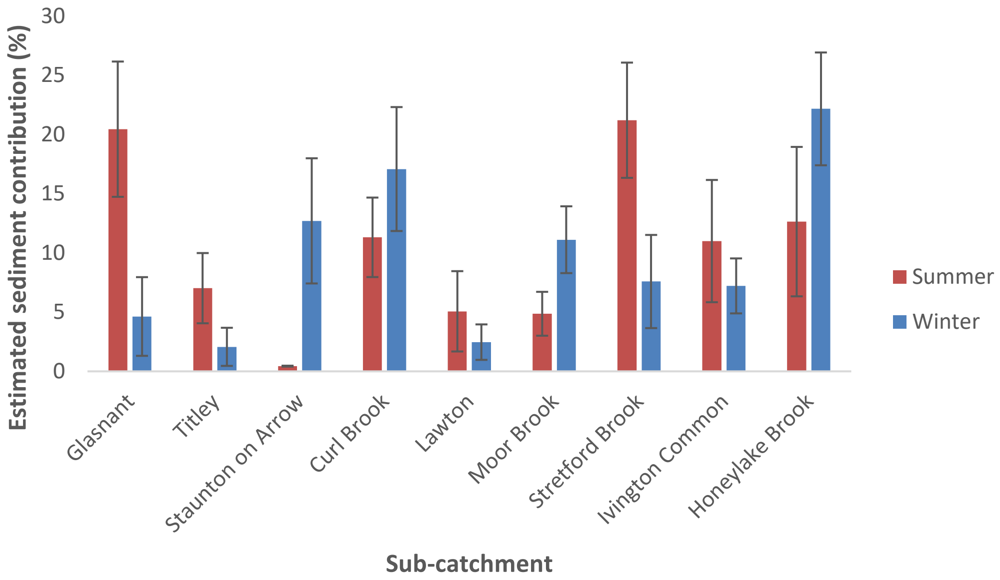

Figure 6.13 Seasonal contrasts in relative sediment contributions and associated standard errors from tributary sub-catchments at the Broadward Farm monitoring site.

The seasonal contrasts in the load-weighted mean relative contributions from each tributary sub-catchment to the suspended sediment samples collected at the Broadward Farm monitoring site is illustrated in Figure 6.14. Overall, the greatest contributions for both the summer and winter period are derived from the lower parts of the Arrow catchment. These contributions are similar for both the summer and winter periods and represent 58 and 55% of the total suspended sediment respectively. Mid-catchment sediment contributions for the winter period are greater than the corresponding contributions for the summer period (40 vs 21%). This is dominated by the high seasonal contrast evident for the un-named tributary at Staunton on Arrow and the Curl Brook sub-catchment, which provide greater winter contributions to the total suspended sediment collected at this monitoring site. In contrast, relative fine sediment inputs from the upper Arrow catchment were greater in the summer compared to the winter (21 vs 5%), which is dominated by the large seasonal contrast in sediment contributions from the Glasnant sub-catchment.

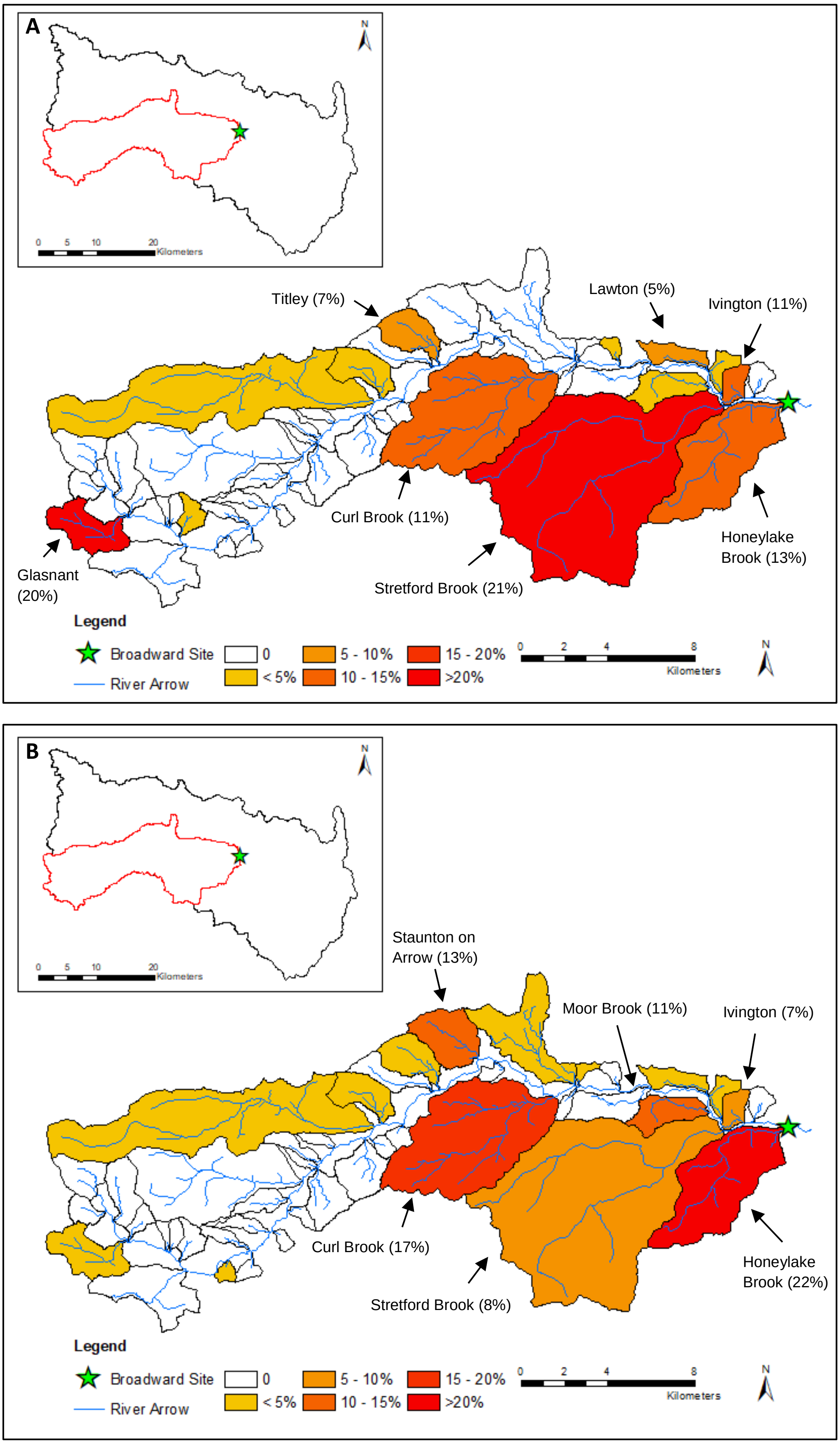

Figure 6.14 Seasonal contrasts in the load-weighted mean relative contributions from each tributary sub-catchment for the Broadward Farm monitoring site in A) summer and B) winter.

6.3.3 Site 3: Eaton Hall Farm

Temporal contrasts in fine sediment contributions from individual tributary sub-catchments to the Eaton Hall Farm monitoring site are presented in Appendix 2.3. Considerable variation in sediment contributions from individual tributary sub-catchments is evident over different sampling periods, with sediment contributions from the Ridgemoor Brook sub-catchment showing the greatest temporal variation. Sediment contributions from this sub-catchment ranged from as little as zero, or so low that it was not recognised by the mixing model, to a peak of 71% during the 17/08/11-28/09/11 sampling period. Furthermore, this sub-catchment represented the dominant source of fine sediment in eight of the 14 events between August 2009 and November 2011, with contributions greater than 30%. In addition, the Cheaton Brook sub-catchment displayed significant temporal variation in sediment contributions. It is evident that this sub-catchment contributes to the total suspended sediment at the Eaton monitoring site during every sampling event, ranging from 2% for the 07/09/10-21/10/10 sampling period to 64% for the 17/03/10-31/05/10 sampling period.

Figure 6.15 shows seasonal contrasts in the load-weighted relative contributions from the most dominant tributary sub-catchments to the suspended sediment flux at the Eaton Hall Farm monitoring site. Contributions from the majority of the main sub-catchment sources are greatest during the summer season, with the greatest contribution identified from the Cheaton Brook sub-catchment (27±6%). The highest contribution during the summer season was 64% for the 17/03/10-31/05/10 sampling period, whereas the highest winter contribution was 44% for the 09/09/09-25/02/10 sampling period (Appendix 2.3). The greatest seasonal contrast with a higher summer contribution was identified from an un-named tributary at Pilleth. Fine sediment contributions were estimated to be 14±4% during the summer season and less than 1% in the winter months (Figure 6.15). It is evident that this distinct contrast is driven by three individual events between June and August 2011 and March and August 2012 with contributions ranging from 22% to 26%. Similarly, a pronounced seasonal contrast is evident for the Cascob Brook sub-catchment with a higher relative load-weighted contribution during the summer season

(7±2 vs 0%). However, this is dominated by only one individual sampling event (09/03/12-22/05/12), with a relatively high contribution of 22% (Appendix 2.3).

In contrast, contributions from three of the main sub-catchment sources are greatest during the winter season (Figure 6.15), with the greatest contribution and seasonal contrast identified in the Ridgemoor Brook sub-catchment (23±8 vs 7±6%). Maximum contributions from both the winter and summer seasons were 71% for the 28/09/11-08/11/11 and 17/08/11-28/09/11 sampling periods respectively. However, this sub-catchment persistently contributed to the total suspended sediment collected at the Eaton monitoring site during the winter sampling periods, with contributions generally higher than 10%, whereas sporadic high contributions were evident during particular summer sampling periods (Appendix 2.3). Similarly, an un-named tributary at Eyton displays a pronounced seasonal variation in fine sediment contribution to the Eaton monitoring site, with a greater contribution associated with the winter season (Figure 6.15). Fine sediment contributions were estimated to be 11±3% during the winter season and less than 1% in the summer months. The highest contribution during the winter season was 25% for the 30/12/11-09/02/12 sampling period, whereas the highest summer contribution was only 2% for the 22/05/12-09/08/12 sampling period. However, this distinct contrast is driven by only two individual sampling events between November 2011 and February 2012 with contributions of more than 20%.

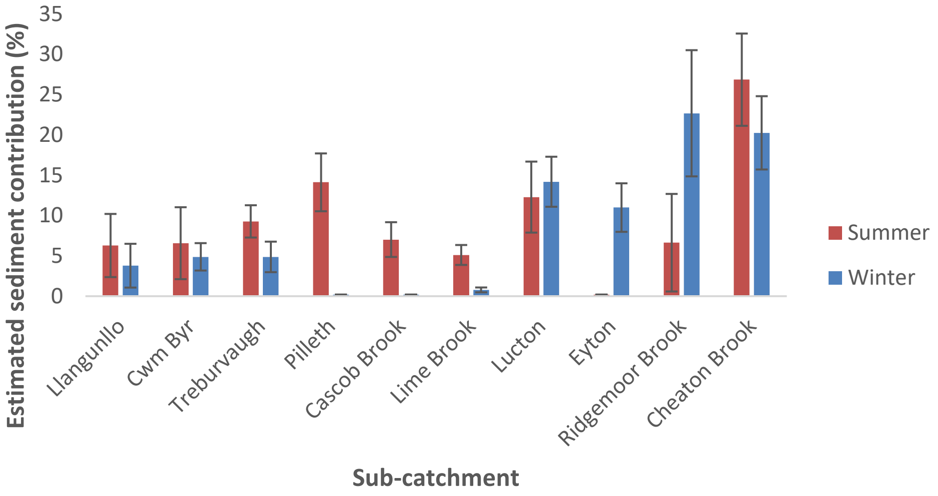

Figure 6.15 Seasonal contrasts in relative sediment contributions and associated standard errors from tributary sub-catchments at the Eaton Hall Farm monitoring site.

Figure 6.16 illustrates the seasonal contrasts in the load-weighted mean relative contributions from each tributary sub-catchment to the suspended sediment samples collected at the Eaton Hall Farm monitoring site. Overall, the greatest contributions for both the summer and winter period are derived from the lower parts of the drainage basin. Contributions from these sources for the winter period are greater than the corresponding contributions for the summer period (71 vs 46%). This is dominated by the high seasonal contrast evident for the Ridgemoor Brook sub-catchment and the un-named tributary at Eyton, which provide greater winter contributions to the total suspended sediment collected at this monitoring site. Contributions derived from headwater sources are similar for both the summer and winter periods and represent 26 and 20% of the total suspended sediment respectively, whereas contributions from mid-catchment sources are greater in the summer season (28 vs 9%). This is largely dominated by the seasonal contrasts seen in the relative contributions from the un-named tributary at Pilleth and the Cascob Brook sub-catchment, providing greater winter contributions.

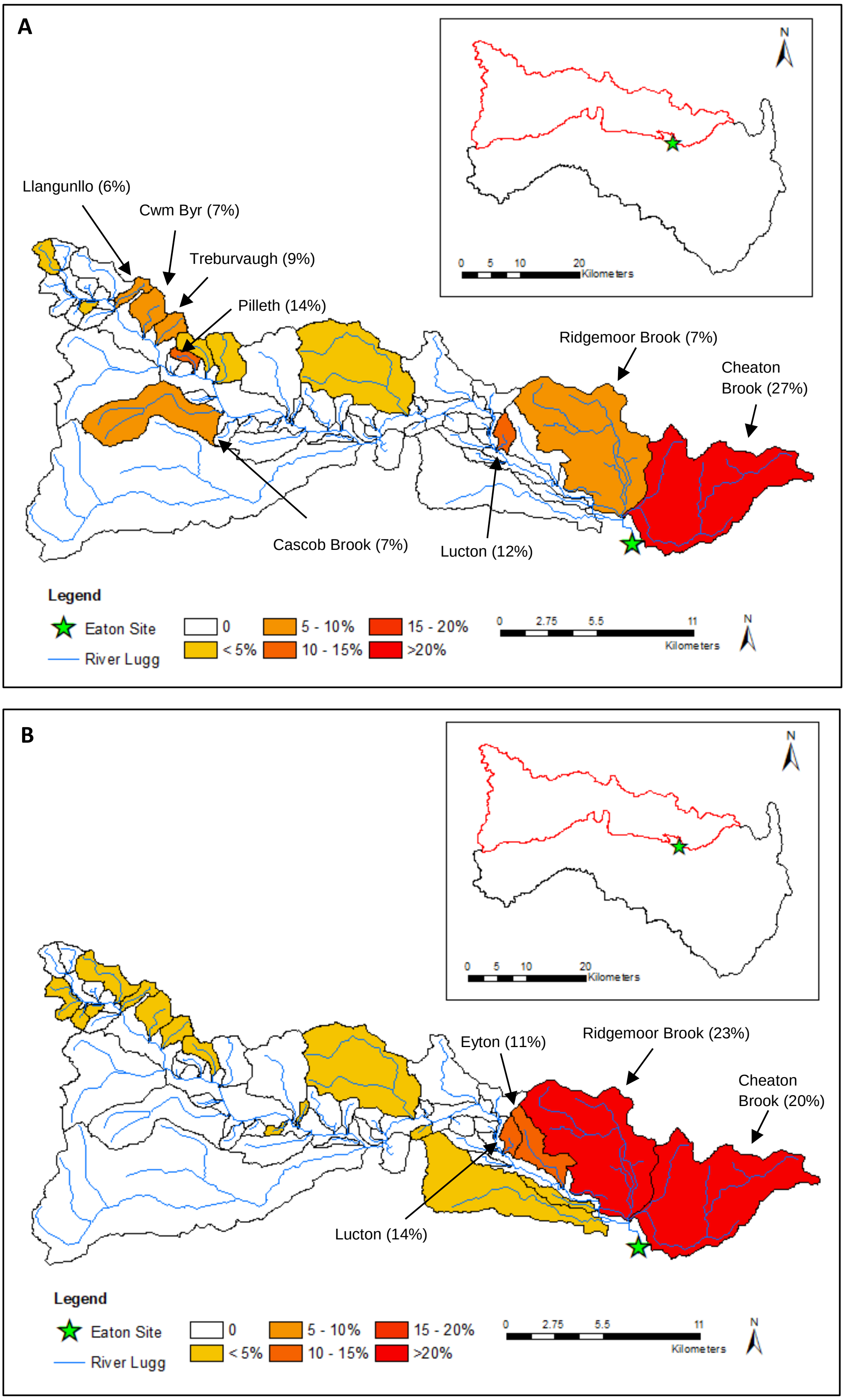

Figure 6.16 Seasonal contrasts in the load-weighted mean relative contributions from each tributary sub-catchment for the Eaton Hall Farm monitoring site in A) summer and B) winter.

6.3.4 Site 4: Marlbrook Farm

The temporal contrasts in fine sediment contributions from individual tributary sub-catchments to the Marlbrook Farm monitoring site are detailed in Appendix 2.4. Sediment contributions from individual sub-catchments vary significantly over different sampling events, with sediment contributions from the Ridgemoor Brook sub-catchment showing the greatest temporal variation. Sediment contributions from this sub-catchment ranged from as little as zero, or so low that it was not recognised by the mixing model, to a peak of 73% during the 09/02/12-03/03/12 sampling period. However, this sub-catchment only represented the dominant source of fine sediment in three individual events, with contributions greater than 30%.

Seasonal contrasts in the load-weighted relative contributions from the most dominant tributary sub-catchments to the suspended sediment flux at the Marlbrook Farm monitoring site are illustrated in Figure 6.17. In contrast to the previous monitoring sites, contributions from most of the main sub-catchment sources are greatest during the winter season, with the greatest contributions identified from the Curl Brook sub-catchment (11±4%). For this sub-catchment, the highest contribution during the winter season was 40% for the 21/09/09-25/02/10 sampling period. However, the greatest summer contribution was 52% for the 17/03/10-31/05/10 sampling event. Although this maximum contribution is greater in the summer season, it is evident that contributions rarely exceeded 5% for all other sampling periods during this season. The greatest seasonal contrast with a higher winter contribution was identified from the Moor Brook sub-catchment (11±3 vs 6±2%). Contributions in all five winter sampling periods where this sub-catchment contributes to the total suspended sediment at the monitoring site were greater than 10%, ranging from 13 to 21% for the 21/10/10-07/12/10 and 07/09/10-21/10/10 sampling periods respectively. Summer contributions only occurred during two individual sampling events between March and August 2012 with contributions ranging from 4 to 16% (Appendix 2.4). Similarly, an un-named tributary at Lucton displays a pronounced seasonal variation in fine sediment contribution to the Marlbrook monitoring site, with a greater contribution associated with the winter season (Figure 6.17). Fine sediment contributions were estimated to be 9±3% during the winter season and 4±1% in the summer months. The highest contribution during the winter season was 21% for the 08/11/11-30/12/11 sampling period, whereas the highest summer contribution was only 7% for the 22/05/12-09/08/12 sampling period.

In contrast, contributions from four of the main sub-catchment sources are greatest during the summer season (Figure 6.17), with the greatest contributions and seasonal contrasts identified in an un-named tributary at Treburvaugh and the Honeylake Brook sub-catchment (10±2 vs 3±1% and 10±2 vs 3±2% respectively). For the former sub-catchment, the highest contribution in the summer season was 16% for the 09/03/12-22/05/12 sampling period, whereas the greatest winter contribution was 9% for the 07/09/10-21/10/10 sampling event. However, for the Honeylake Brook sub-catchment maximum contributions from both the summer and winter seasons were 15% for the 22/05/12-09/08/12 and 21/10/10-07/12/10 sampling periods respectively. Although there were a greater number of individual winter sampling events that contributed to the total suspended sediment at this monitoring site, it is evident that this distinct seasonal contrast was driven by two individual summer sampling periods between March and August 2012 with contributions ranging between 13 and 15% (Appendix 2.4). A pronounced seasonal contrast is also evident for the Titley sub-catchment, with a greater contribution associated with the summer season (Figure 6.17). Fine sediment contributions were estimated to be 6±2% during the summer season and 2±1% during the winter season. Although maximum contributions from both the summer and winter seasons were similar (17 and 16% respectively), this sub-catchment persistently contributed to the total suspended sediment collected at the Marlbrook monitoring site during the 2011 and 2012 summer seasons, with contributions generally higher than 10%.

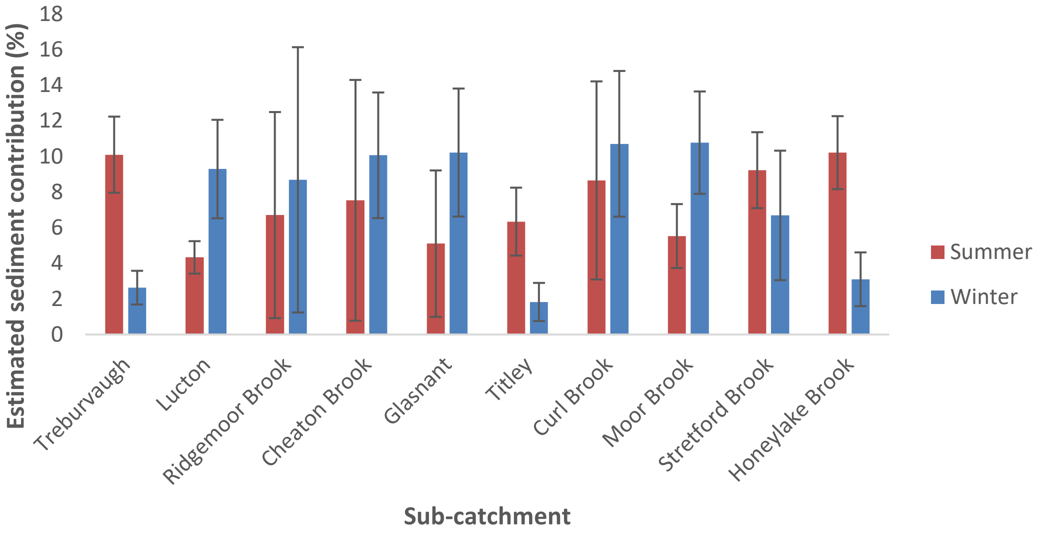

Figure 6.17 Seasonal contrasts in relative sediment contributions and associated standard errors from tributary sub-catchments at the Marlbrook Farm monitoring site.

The seasonal contrasts in the load-weighted mean relative contributions from each tributary sub-catchment to the suspended sediment samples collected at the Marlbrook Farm monitoring site is illustrated in Figure 6.18. Overall, the greatest contributions for both the summer and winter period are derived from the lower parts of the catchment. These contributions are similar for both the summer and winter periods and represent 44 and 45% of the total suspended sediment respectively. Contributions from upper catchment sources for the summer period are greater than the corresponding contributions for the winter period (35 vs 25%), which is dominated by the large seasonal contrast in sediment contributions from the un-named tributary at Treburvaugh. In contrast, relative fine sediment inputs from mid-catchment sources for the winter period are greater than the corresponding contributions for the summer period (28 vs 21%). This is dominated by the high seasonal contrast evident for the Staunton on Arrow and the Curl Brook sub-catchment, which provide greater winter contributions to the total suspended sediment collected at this monitoring site.

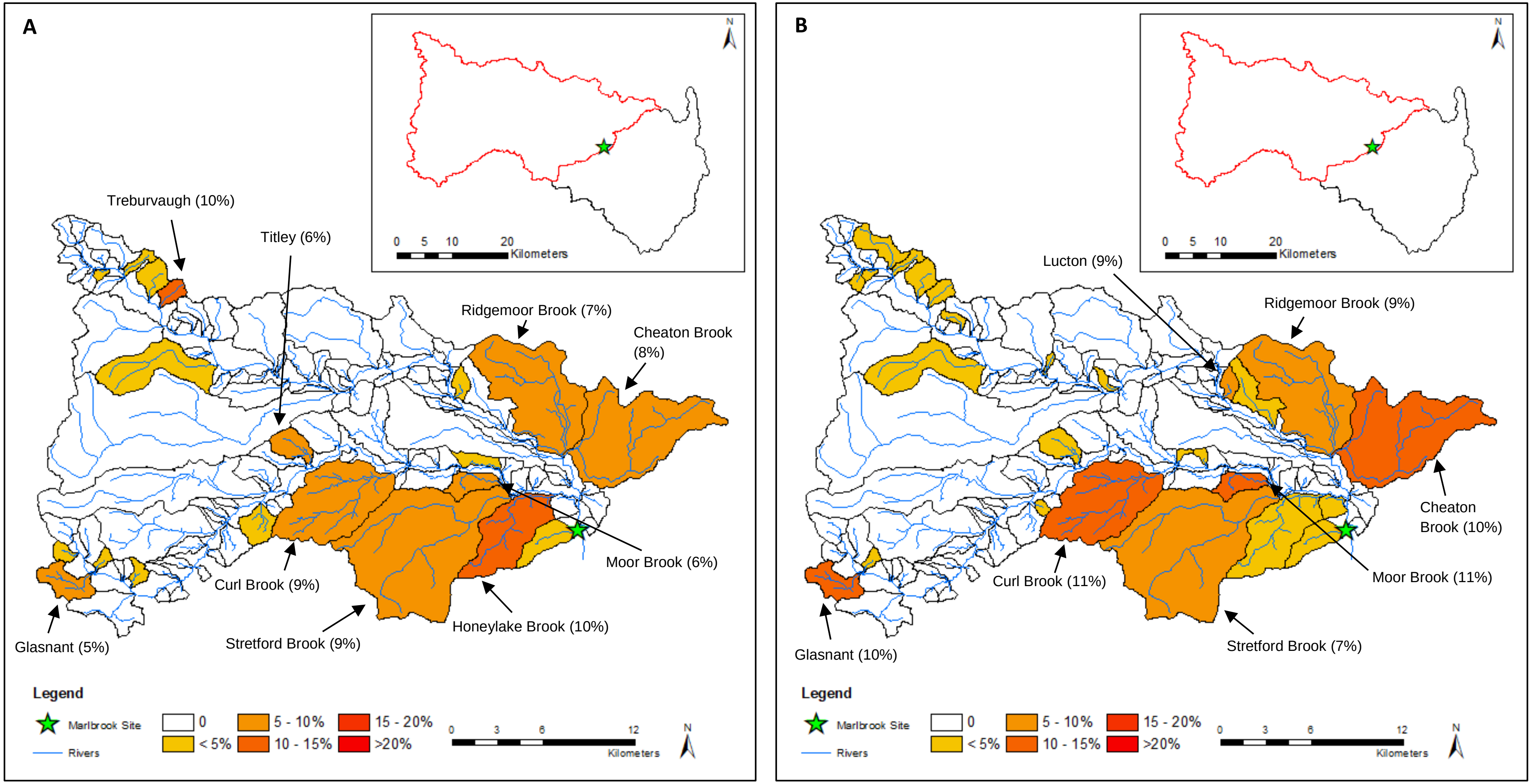

Figure 6.18 Seasonal contrasts in the load-weighted mean relative contributions from each tributary sub-catchment for the Marlbrook Farm monitoring site in A) summer and B) winter.

6.3.5 Site 5: Lugwardine

Temporal contrasts in fine sediment contributions from individual tributary sub-catchments to the Lugwardine monitoring site are presented in Appendix 2.5. Variation in sediment contributions from individual tributary sub-catchments is evident over different sampling periods, with sediment contributions from the Wellington Brook sub-catchment showing the greatest temporal variation. Sediment contributions from this sub-catchment ranged from as little as zero, or so low that it was not recognised by the mixing model, to a peak of 41% during the 17/08/11-28/09/11 sampling period. Furthermore, this sub-catchment represented the dominant source of fine sediment in three of the four events during the 2011 summer period, with contributions greater than 20%. In addition, the Stretford Brook sub-catchment displayed significant temporal variation in sediment contributions. This sub-catchment represented the dominant source of fine sediment in three of the first four events, with contributions ranging from 25% during the 09/09/10-25/10/10 sampling period to 40% during the 17/03/10-31/05/10 sampling period (Appendix 2.5).

Figure 6.19 shows seasonal contrasts in the load-weighted relative contributions from the most dominant tributary sub-catchments to the suspended sediment flux at the Lugwardine monitoring site. Contributions from four of the main sub-catchment sources are greatest during the summer season, with the greatest contribution and seasonal contrast identified from the Little Lugg sub-catchment (16±3 vs 8±3%). The highest contribution during the summer season was 21% for three separate sampling periods, whereas the highest winter contribution was 26% for the 28/09/11-15/11/11 sampling period. Although the greatest contribution of fine sediment occurred during the winter season, all contributions from individual sampling periods during the summer months were more than 10% and ranged from 13 to 21%. Similarly, the Cheaton Brook displays a pronounced seasonal variation in fine sediment contribution to the Lugwardine monitoring site, with a greater contribution associated with the summer season (Figure 6.19). Fine sediment contributions were estimated to be 15±3% during the summer season and 7±2% in the winter months. The highest contribution during the summer season was 24% for the

22/05/12-09/08/12 sampling period, whereas the highest winter contribution was 13% for the 30/12/11-09/02/12 sampling period (Appendix 2.5).

In contrast, contributions from five of the main sub-catchment sources are greatest during the winter season (Figure 6.19), with the greatest contribution and seasonal contrast identified from an un-named tributary at Lucton (9±3 vs 3±1%). The highest contribution during the winter season was 24% for the 15/11/11-30/12/11 sampling period, whereas the greatest summer contribution was only 7% for the 22/05/12-09/08/12 sampling period. Similarly, the Bodenham Brook sub-catchment displays a pronounced seasonal variation in fine sediment contribution to the Lugwardine monitoring site, with a greater contribution associated with the winter season (Figure 6.19). Fine sediment contributions were estimated to be 6±4% during the winter season and less than 1% in the summer months. This distinct contrast is mainly driven by high contributions during two individual sampling events (31/01/11-09/03/11 and 28/09/11-15/11/11), with contributions of 28 and 23% respectively (Appendix 2.5).

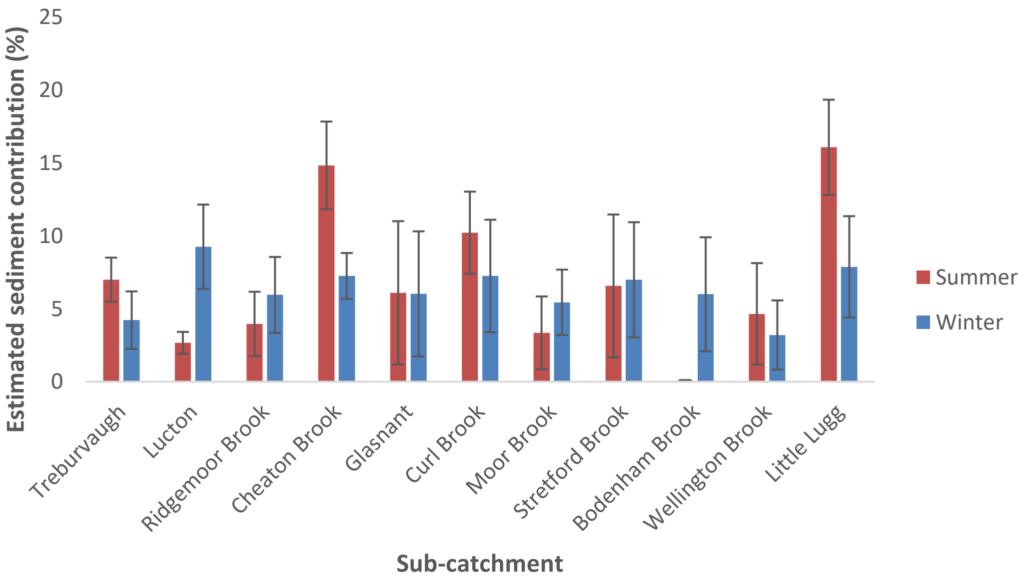

Figure 6.19 Seasonal contrasts in relative sediment contributions and associated standard errors from tributary sub-catchments at the Lugwardine monitoring site.

Figure 6.20 illustrates the seasonal contrasts in the load-weighted mean relative contributions from each tributary sub-catchment to the suspended sediment samples collected at the Lugwardine monitoring site. Overall, the greatest contributions for both the summer and winter period are derived from mid-catchment sources. Contributions from these sources for the winter period are greater than the corresponding contributions for the summer period (57 vs 45%). This is dominated by the high seasonal contrast evident for the un-named tributary at Lucton, which provides greater winter contributions to the total suspended sediment collected at this monitoring site. Contributions derived from the lower parts of the Lugg catchment are similar for both the summer and winter periods and represent 24 and 23% of the total suspended sediment respectively, whereas contributions from the upper parts of the catchment are greater in the summer season (34 vs 20%). This is largely dominated by the seasonal contrasts seen in the relative contributions from the un-named tributary at Treburvaugh, providing greater summer contributions.

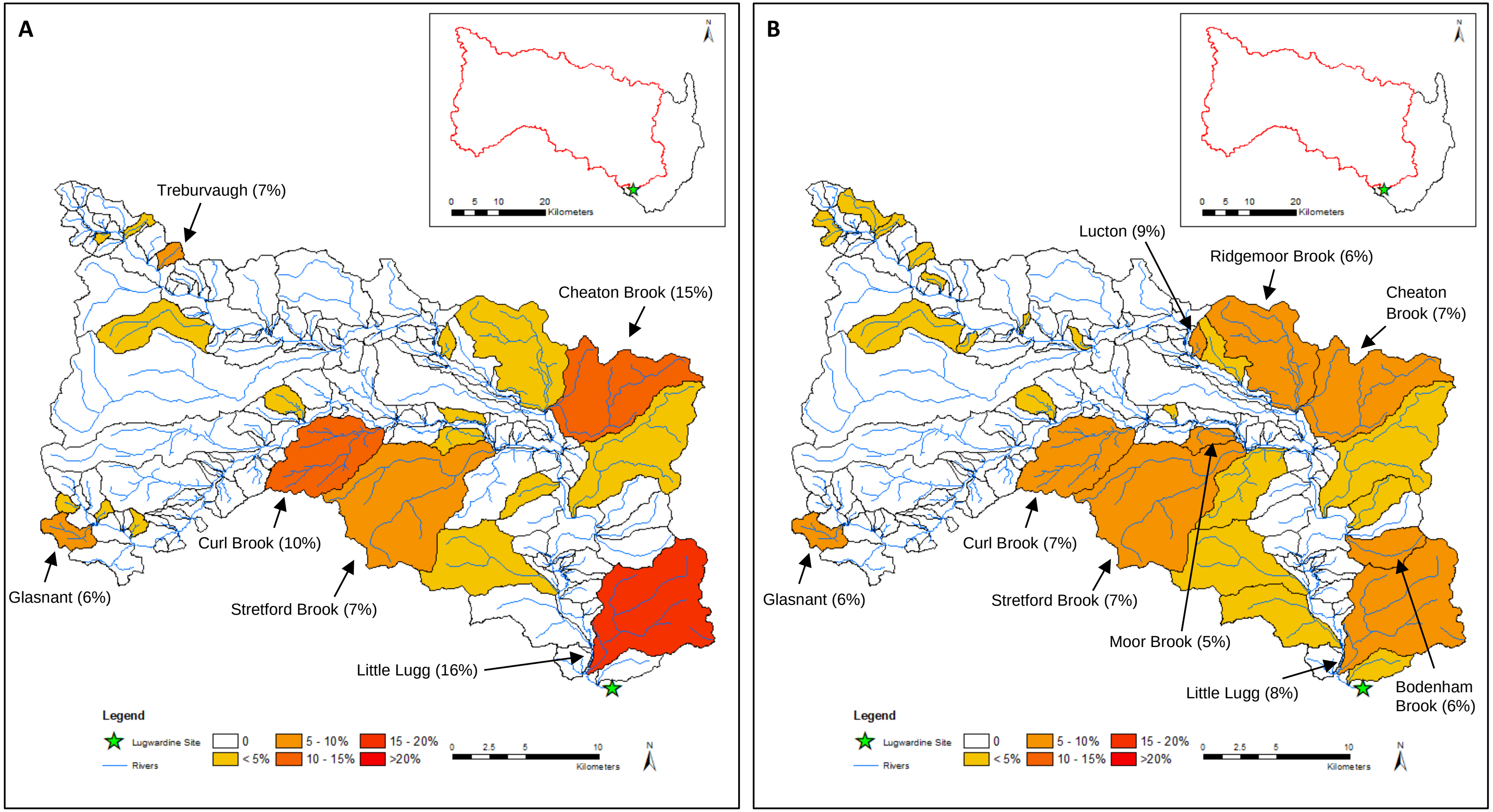

Figure 6.20 Seasonal contrasts in the load-weighted mean relative contributions from each tributary sub-catchment for the Lugwardine monitoring site in A) summer and B) winter.

6.3.6 Summary

The catchment scale source apportionment results have presented significant differences in the importance of various sub-catchment sources during different flow events. These differences have produced pronounced seasonal contrasts in the relative load weighted mean fine sediment contributions at each monitoring site. The seasonal contrasts in the contributions from the most dominant tributary sub-catchments that persistently deliver sediment to sink sites within the Lugg catchment are shown in Table 6.2. In general, the number of dominant tributary sub-catchments showing greatest contributions over the different seasons are similar. However, most of the dominant sub-catchment sources contributing to the total suspended sediment at the Marlbrook monitoring site are greatest during the winter season. Only the Glasnant, Ridgemoor and Cheaton Brook sub-catchments show a pronounced seasonal contrast where contributions are more dominant in the summer season. Nevertheless, this seasonal pattern was not consistent for all sub-catchments. For instance, whilst the un-named tributary at Lucton and the Moor and Honeylake Brook sub-catchments are more dominant in the winter season at all three monitoring sites where it contributes to the total suspended sediment, the Glasnant and Cheaton Brook sub-catchments are more dominant in the summer season.

The greatest seasonal contrast in the dominant sub-catchments was shown for contributions from the Ridgemoor Brook sub-catchment at the Eaton Hall Farm monitoring site. Relative fine sediment contributions were greater in the winter season in comparison to the summer period (23±8 vs 7±6). In contrast, the two other monitoring sites downstream in the Lugg catchment show smaller contrasts, with summer contributions greater at Marlbrook and contributions in the winter season greater at Lugwardine (Table 6.2). However, as sediment transit times are not accounted for during the mixing model process, it is imperative to recognise that these seasonal contributions relate to sediment output during individual periods, rather than its original mobilisation within the drainage basin (Walling *et al.,* 2008). It is possible that sediment mobilised from a particular sub-catchment source and transferred to the channel during one season is stored, remobilised and transported to the catchment outlet during the following season (Svendsen and Kronvang, 1995, Walling and Amos, 1999).

Table 6.2 Seasonal contrasts in the estimated sediment contributions of the most persistent sources of fine sediment at each monitoring site.

Tributary sub-catchment	Estimated sediment contributions (%)									
	Site 1: Hunton		Site 2: Broadward		Site 3: Eaton		Site 4: Marlbrook		Site 5: Lugwardine	
	W	S	W	S	W	S	W	S	W	S
Glasnant	12±5	13±10	5±3	20±6			3±1	10±2	6±4	6±5
Curl Brook			17±5	11±3			9±3	4±1	7±4	10±3
Moor Brook			11±3	5±2			9±7	7±6	5±2	3±2
Stretford Brook			8±4	21±5			10±4	8±7	7±4	7±5
Honeylake Brook			22±5	13±6			10±4	5±4	2±1	0±0
Treburvaugh					5±2	9±2	11±4	9±6	4±2	7±2
Lucton					14±3	12±4	11±3	6±2	9±3	3±1
Ridgemoor Brook					23±8	7±6	7±4	9±2	6±3	4±2
Cheaton Brook					20±5	27±6	3±2	10±2	7±2	15±3
Little Lugg									16±3	8±3

(W) winter (S) summer

6.4 Discussion

The catchment scale sediment source apportionment process has identified several individual tributary sub-catchments that persistently contribute fine sediment to the five sink sites situated in the Lugg catchment. The observed spatial and temporal variations in relative source type contributions are likely to reflect a number of factors that control variations in sediment mobilisation and delivery from individual source types. These factors include variations in catchment area and the spatial distribution of source areas; elevation and slope across the study catchment; the underlying soil type of individual source areas; land use activities and land cover; inter-storm variations in the magnitude and intensity of precipitation; proximity of source areas to sampling points; and localised catchment events (Collins *et al.,* 1997c, Walling *et al*., 1999b, Collins *et al*., 2001).

Although Walling and Collins (2005) reported that catchment size can exert a significant influence on the extent of sediment contributions, existing evidence suggests that factors other than catchment size influences sediment delivery (Lu *et al.,* 2005). When considering the catchment area of each tributary sub-catchment, the apportionment results demonstrate that the significance of relative source contributions generally do not reflect the associated spatial extent. For instance, at the Hunton monitoring site the greatest load-weighted fine sediment contributions are estimated to be derived from tributary sub-catchments with catchment areas less than 1 km², whilst the sub-catchment with the greatest catchment area (32.9 km²) is estimated to contribute less than 10% to the total suspended sediment (Figure 6.21a). This is likely to reflect a diminishing sediment supply associated with dilution from a greater base flow in the latter sub-catchment (Guzman *et al.,* 2013). Similarly, for the Broadward, Marlbrook and Lugwardine monitoring sites, the greatest source contributions were not predicted for the tributary sub-catchments with the greatest catchment areas. This indicates that there is no relationship between differences in the relative importance of catchment sediment sources and catchment size, suggesting that additional factors are at play in controlling sediment loss from individual sub-catchment sources.

However, this general pattern is not evident when determining the controls on sediment mobilisation and delivery at all sink sites in the Lugg catchment. At the Eaton monitoring site, the two sub-catchments with the greatest load-weighted fine sediment contributions are estimated to be derived from tributary sub-catchments with the largest catchment areas (Figure 6.21b). Nevertheless, an un-named tributary at Lucton, with a catchment area of only 1.9 km² also contributes a high amount of sediment, whilst the Cascob and Lime Brook sub-catchments contribute less than 5% to the total suspended sediment with relatively large catchment areas. Therefore, areal extent alone may not necessarily account for the spatial variations in relative fine sediment contribution at this site.

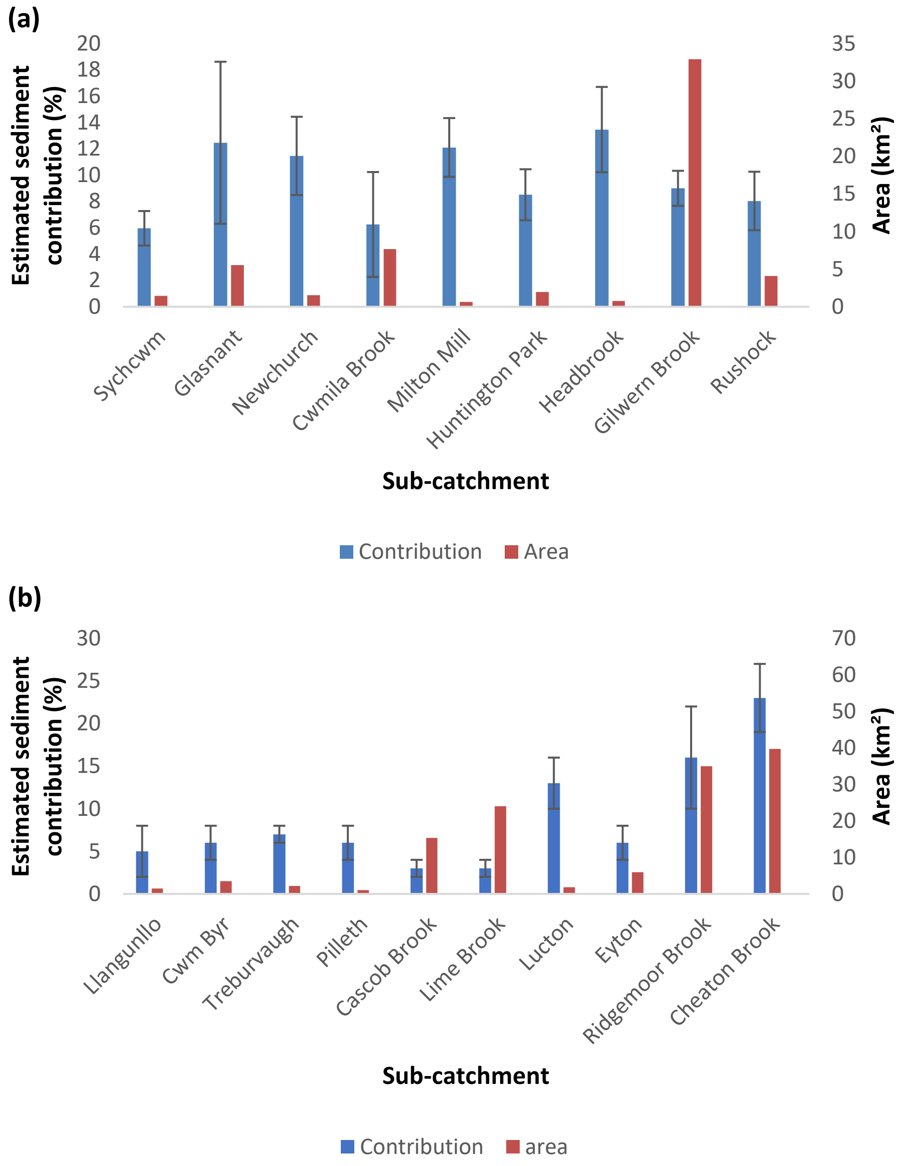

Figure 6.21 Catchment area and the associated relative sediment contributions from each of the dominant tributary sub-catchments at (a) the Hunton Bridge monitoring site and (b) the Eaton Hall Farm monitoring site.

Differences in the topography (slope and elevation) across the study catchment could also have an important influence on the sources of sediment and the associated spatial variations in sediment provenance (Lintern *et al.,* 2018). When considering the elevation of the sub-catchments that persistently deliver fine sediment to the monitoring sites, it is evident that the majority of them are situated in the mid to lower parts of the Lugg catchment characterised by low elevation (Figure 6.22). Between 54 and 58% of the load-weighted mean source contributions at the Lugwardine and Marlbrook monitoring sites was sourced from these lowland sub-catchments, which are characterised by average slopes ranging from 2.6 to 6.9% (Table 6.3). When taking into account all the other sub-catchments that contribute sediment, it is evident that lowland erosion was a more important source of sediment than the upland areas, with contributions as high as 67% at the Lugwardine monitoring site and 64% at the Marlbrook site. In contrast, only two of the most persistent contributors of fine sediment (Glasnant and Treburvaugh) are located in the upper parts of the catchment with high elevation (Figure 6.22). Although these sub-catchments are associated with larger average slopes ranging from 15.6 to 17% (Table 6.3), they only contribute 11 and 13% of the load-weighted mean suspended sediment sampled at the Lugwardine and Marlbrook monitoring sites. This suggests that although slope and elevation have an influence on the sources of sediment, it does not fully reflect the variations in sediment contributions. This is highlighted by Ayele *et al.* (2017) who found that variation in sediment yield was more sensitive to land use and the prevailing soil type regardless of the terrain slope. Therefore, it is important that these additional factors are considered.

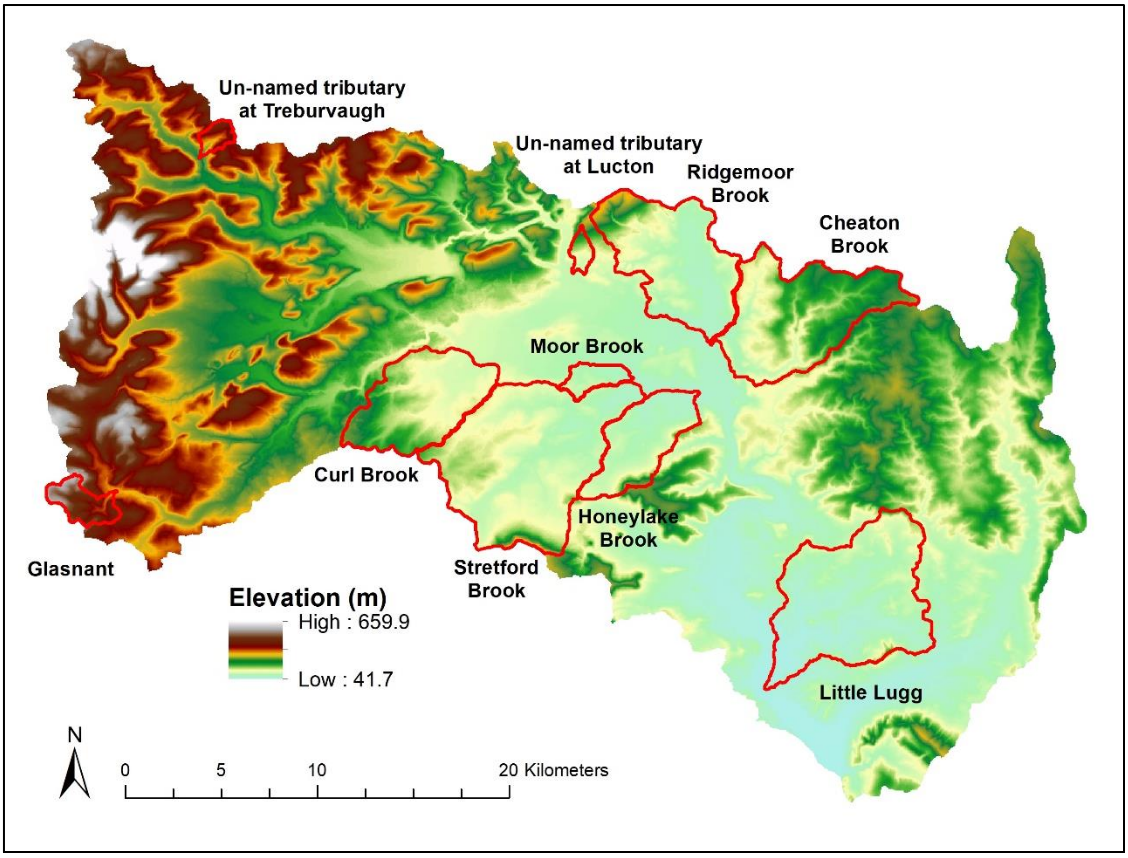

Figure 6.22 Digital Elevation Model of the Lugg catchment showing the elevation of the sub-catchments identified as the most persistent sources of sediment (OS data © Crown copyright and database rights 2018).

Table 6.3 The slopes associated with the sub-catchments identified as the most persistent contributors of sediment**.**

Tributary sub-catchment	Maximum slope (%)	Average slope (%)
Glasnant	56.2	15.6
Curl Brook	26.5	4.3
Moor Brook	9.2	2.6
Stretford Brook	45.7	4.2
Honeylake Brook	46.4	4.8
Treburvaugh	49.0	17.0
Lucton	23.1	6.9
Ridgemoor Brook	45.8	5.6
Cheaton brook	28.3	6.4
Little Lugg	33.9	4.1

The relative importance of catchment sources and associated spatial variations in sediment provenance can also be determined by the soil type and underlying geological characteristics of source areas (Miller *et al*., 2013). When considering the soil type and associated geological characteristics prevalent in the sub-catchments that persistently deliver fine sediment to the monitoring sites, it is evident that most of them are characterised by argillic brown earths (Figure 6.23). The pedogenic characteristics of this soil type are strongly influenced by the underlying Old Red Sandstone bedrock and are particularly erodible during heavy rainfall events (see Chapter 2, section 2.4). Therefore, it is not surprising that many of the most dominant sub-catchments contributing high amounts of fine sediment are underlain by these characteristics. However, the un-named tributary at Treburvaugh and the Glasnant sub-catchment are characterised by less erosive soils, despite being associated with high sediment contributions. This suggests that the soil type and characteristics of source areas may not fully reflect variations in sediment contributions from different sub-catchments.

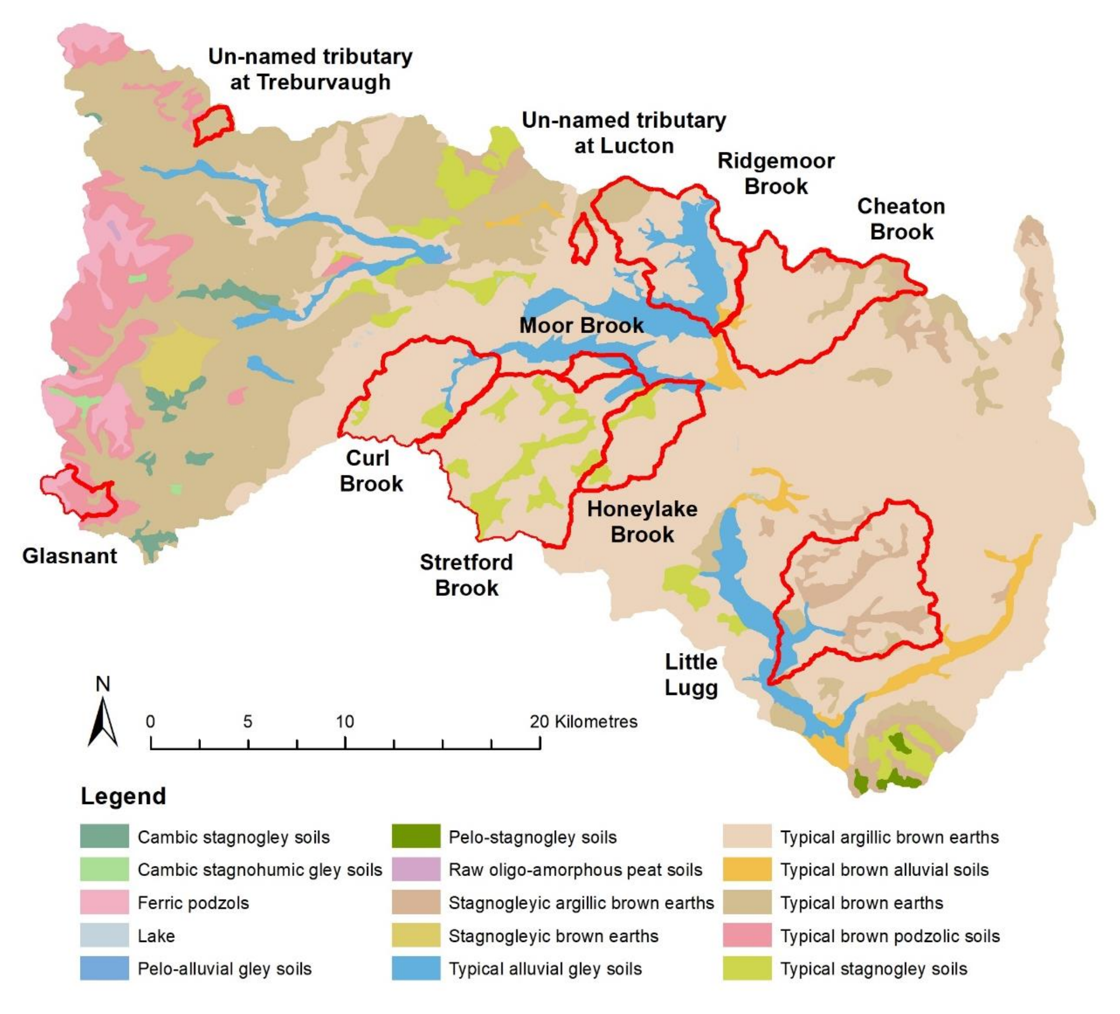

Figure 6.23 Soil type associated with the most dominant sub-catchments in the Lugg catchment (© Cranfield University (NSRI) and for the controller of HMSO 2012).

In addition to catchment size and soil type, variations in land cover and land use activities and may have an influence on the spatial and temporal variations associated with sediment contributions from individual tributary sub-catchments. Sediment contributions from agricultural surface soils are understood to be an important source of environmental degradation and water quality problems including those associated with enhanced soil loss and sediment loadings (Collins *et al.,* 1997a; Evans, 1998; Kurz *et al.,* 2006; Dewry *et al*., 2008; Collins *et al*., 2010a; Lamba *et al.,* 2015). The land use within the Lugg catchment is mainly dominated by agriculture, with grassland dominating the upper reaches and arable cultivation the main agricultural activity in the lowland areas (see Chapter 2, Section 2.5). Variations in land use activities could represent an important control determining the relative importance of sediment sources

It is therefore important to put these into context when interpreting the source apportionment results. Table 6.4 details the timings of land management and farming practices in the Lugg catchment. It shows the timings of main activities associated with the main crop types. For most crops, bare ground follows harvesting during the autumn and winter months which is when soils are most susceptible to erosion during rainfall events. Field preparation also occurs during these high-risk times. This is particularly evident for maincrop potatoes, where the main farming activities of harvesting and field preparation occur between October and April. In addition, these activities occur between September and March for soft fruit production.

Table 6.4 Calendar of land management and farming practices in the Lugg catchment.

Crop	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
Winter Wheat	🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟫	🟫	🟫
Winter Barley	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟫	🟫	🟧
Winter Oats	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟫	🟫	🟧
Spring Cereals	🟫	🟫	🟫	🟧	🟩	🟩	🟩	🟩	🟥	🟫	🟫	🟫
Spring Oilseed Rape	🟫	🟫	🟫	🟧	🟩	🟩	🟩	🟩	🟥	🟥	🟫	🟫
Winter Oilseed Rape	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟫	🟧	🟩	🟩
Maincrop potatoes	🟫	🟫	🟫	🟧	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟫
Early potatoes	🟫	🟫	🟧	🟩	🟩	🟩	🟥	🟫	🟫	🟫	🟫	🟫
Spring Field Beans	🟫	🟫	🟧	🟩	🟩	🟩	🟩	🟩	🟥	🟫	🟫	🟫
Winter Field Beans	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟫	🟫	🟫	🟧
Dried Peas	🟫	🟫	🟫	🟧	🟩	🟩	🟩	🟥	🟫	🟫	🟫	🟫
Maize	🟫	🟫	🟫	🟫	🟧	🟩	🟩	🟩	🟩	🟥	🟫	🟫
Fodder crops	🟫	🟫	🟫	🟫	🟫	🟧	🟩	🟩	🟩	🟥	🟥	🟥
Soft Fruit	🟫	🟧	🟧	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟫	🟫
Hops	🟫	🟧	🟧	🟩	🟩	🟩	🟩	🟩	🟥	🟫	🟫	🟫
Grass (hay)	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩
Grass (silage)	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩
Activity												
Field preparation	🟧	**Field cover**	🟩	**Harvest**	🟥	**Bare ground**	🟫					

It is also necessary to place the sediment source apportionment results in context with the land use characteristics of individual sub-catchments. Previous research suggests that dominant sediment contributors would reflect, at least in part, the prevailing land use characteristics (Collins *et al.,* 2010b). It is evident that the larger sediment contributions at the Eaton monitoring site are associated with sub-catchments with greater arable land coverage (Figure 6.24a). For instance, the Cheaton and Ridgemoor Brook sub-catchments are the greatest contributors of fine sediment and have the largest area of land classified as arable (47 and 44% respectively). The activities associated with this land use, for example, intensive potato cultivation and the dominance of autumn-sown cereals would suggest a high erosion risk and subsequent fine sediment delivery to the channel network (Walling *et al*., 1999a; Walling 2005; Collins and Walling 2007a; Collins *et al*., 2010b). In contrast, sub-catchments located in the upper parts of the catchment, associated with smaller sediment contributions (3-7%), are dominated by grassland which is mainly utilised for livestock production, particularly sheep farming.

However, this pattern does not transpire at the other monitoring sites which is most notable at the Lugwardine monitoring site. Although the tributary sub-catchment with the greatest estimated sediment contribution is associated with the largest area of land classified as arable (67%), the Wellington and Moor Brook sub-catchments are predicted to contribute small proportions of fine sediment, despite being dominated by arable cultivation (Figure 6.24b). Furthermore, an un-named tributary at Lucton provides relatively high proportions of fine sediment, yet only 37% of the land area is classified as arable. This indicates that factors in addition to spatial coverage of land use control sediment mobilisation and delivery.

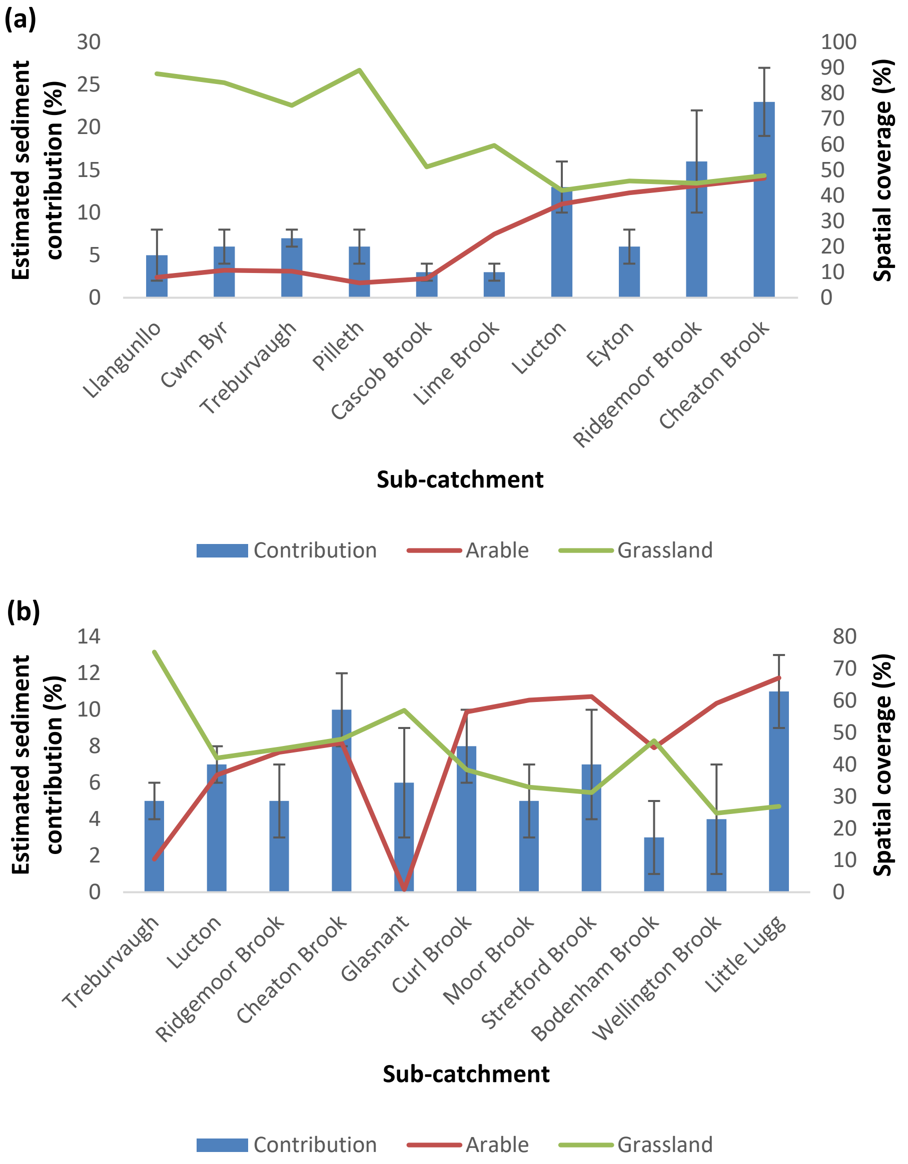

Figure 6.24 Estimated sediment contributions and associated spatial coverage of arable and grassland from the dominant tributary sub-catchments at (a) the Eaton Hall Farm monitoring site and (b) the Lugwardine monitoring site *(Land Cover Map 2007 data).*

These factors could include land use characteristics like for example, the location of high risk fields within individual tributary sub-catchments and the connectivity between them and the river channel network, the timing of land use activities and the type of crop cover. It was apparent through field reconnaissance that intensive arable farming, in particular potato cultivation, was located adjacent to the river channel network in the un-named tributary sub-catchment at Lucton. This large field was located close to the channel outlet and was characterised by small channel margins with evidence of major sediment runoff and deposition (Figure 6.25). This therefore, could reflect the relatively large contributions from this individual tributary sub-catchment despite the land cover not being dominated by arable cultivation.

Figure 6.25 Runoff and fine sediment deposition from potato field adjacent to un-named tributary at Lucton (29th June 2011).

When considering the seasonal variations associated with fine sediment contributions from this tributary sub-catchment, it is evident that greater contributions were associated with the winter season when erosion of bare tilled soils associated with arable cultivation would be at a maximum. For instance, the greatest contributions from this sub-catchment at the Marlbrook and Lugwardine monitoring sites were 21 and 24% respectively for the period immediately succeeding harvesting activities (Table 6.4) within the catchment (November-December 2011). These activities leave soil in a condition highly susceptible to erosion (Rasmussen, 1999), which is particularly evident after potato harvesting, where soils become compact reducing the porosity, limiting water infiltration and subsequently increasing sediment runoff. This sub-catchment source also contributes a high amount of suspended sediment at the Marlbrook monitoring site during the period January-March 2011 (Appendix 2.4). This period coincides with field preparation (Table 6.4) which involves deep ploughing and de-stoning prior to potato planting. However, as potatoes are a very intensive crop they are commonly rotated with maize or winter cereal in the Lugg catchment. Blake *et al*., (2012) attempted to trace crop-specific sediment sources in the River Otter and reported that sediment mobilisation and delivery varies under different crop regimes. They identified that maize is similarly associated with an increased risk of soil erosion with a rapid runoff and erosional response to rainfall events (Boardman *et al*., 2009; Hogan *et al*., 2009). Therefore, at the Eaton monitoring site, the greatest contributions from this tributary sub-catchment occurred between October and December 2010 (Appendix 2.3).

The Lugg catchment is also important for commercial production of soft fruit under polytunnels (Kemble 2015), which lowers the infiltration capacity of the surface soil and accelerates runoff response in concentrated areas (Defra, 2010). Targeted field reconnaissance identified large areas of soft fruit production around Brierley, which can be associated with large amounts of fine sediment delivered from the Honeylake Brook sub-catchment (Figure 6.26). It is evident that this tributary sub-catchment is the most dominant source of fine sediment at the Broadward monitoring site, with a load-weighted mean contribution of 19±4% (Figure 6.3). Significant contributions from this source area were associated with the period immediately before and succeeding this land use activity, with the highest contributions ranging from 31 and 42% between February and April 2011 (Appendix 2.2). This period coincides with field preparation, installation of plastic and polytunnel establishment (Table 6.4) which is the most vulnerable time for runoff and soil erosion. Sediment contributions were also high between September and November 2011 succeeding harvesting activities, leaving bare tilled soils susceptible to erosion.

Figure 6.26 Fine sediment mobilisation and runoff from soft fruit production under polytunnels near Brierley, Herefordshire (April 2008, *Sarah Olney CSFO*).

However, it is evident that contributions from this tributary sub-catchment are high throughout the growing season (May-September), with contributions ranging from 43 to 51% (Appendix 2.2). Given the dominance of arable land and soft fruit production under polytunnels in this sub-catchment, it is surprising that although load-weighted winter contributions are higher (Figure 6.13), the greatest individual temporal contributions are associated with the summer period. Nevertheless, these complex temporal variations are likely to reflect differences in the magnitude and intensity of precipitation and its spatial distribution and therefore provides an additional control determining the relative importance of catchment sediment source areas. It is evident that the 2011 summer period coincided with a number of rainfall events with accumulations greater than 10 mm and an extreme event with a daily accumulation of more than 26 mm. This was the highest daily rainfall accumulation throughout the whole of the 2010-2011 hydrological year (Figure 6.27). The associated relative contribution of fine sediment from the Honeylake Brook sub-catchment at the Broadward monitoring site was 43% (April-June 2011). The low infiltration capacity and pathways for enhanced sediment transport associated with polytunnels suggests that high intensity summer storm events would dramatically increase sediment runoff and therefore, provide relatively high contributions to the monitoring site during these periods.

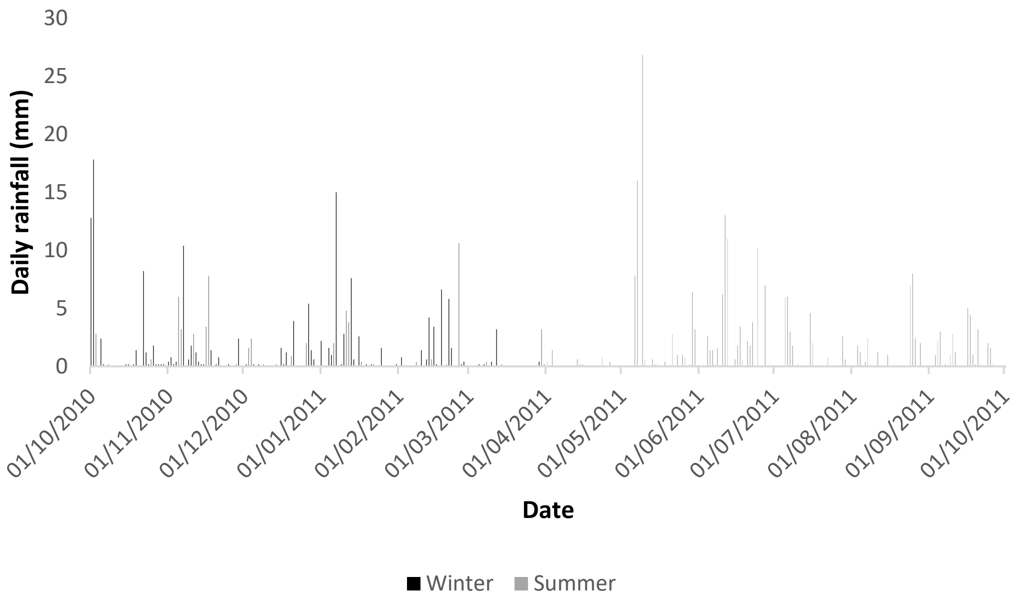

Figure 6.27 Daily rainfall accumulations for the 2010-2011 water year (*Leominster gauging station, Environment Agency 2013*).

In addition, this temporal pattern in contributions of fine sediment was also evident for tributary sub-catchments located in the upper parts of the Lugg catchment. The greatest contributions of fine sediment from an un-named tributary at Treburvaugh occur during two individual sampling events between March and August 2012. At the Marlbrook monitoring site, contributions ranged from 13 to 16% over this period, whereas the greatest contribution prior to this was only 9% (Appendix 2.4). Similarly, at the Eaton monitoring site, contributions from this source area ranged from 14 to 16% for the same period. Furthermore, fine sediment contributions from the Cascob Brook sub-catchment at the Eaton monitoring site were isolated to one individual sampling period between March and May 2012, with an estimated contribution of 22% (Appendix 2.3). When considering the magnitude and intensity of precipitation throughout individual sampling periods, it is evident that the highest intensity rainfall over the whole monitoring period occurred during these sampling events (Figure 6.28). These high intensity storm events coincided with the wettest April-June on record (Met Office 2012).

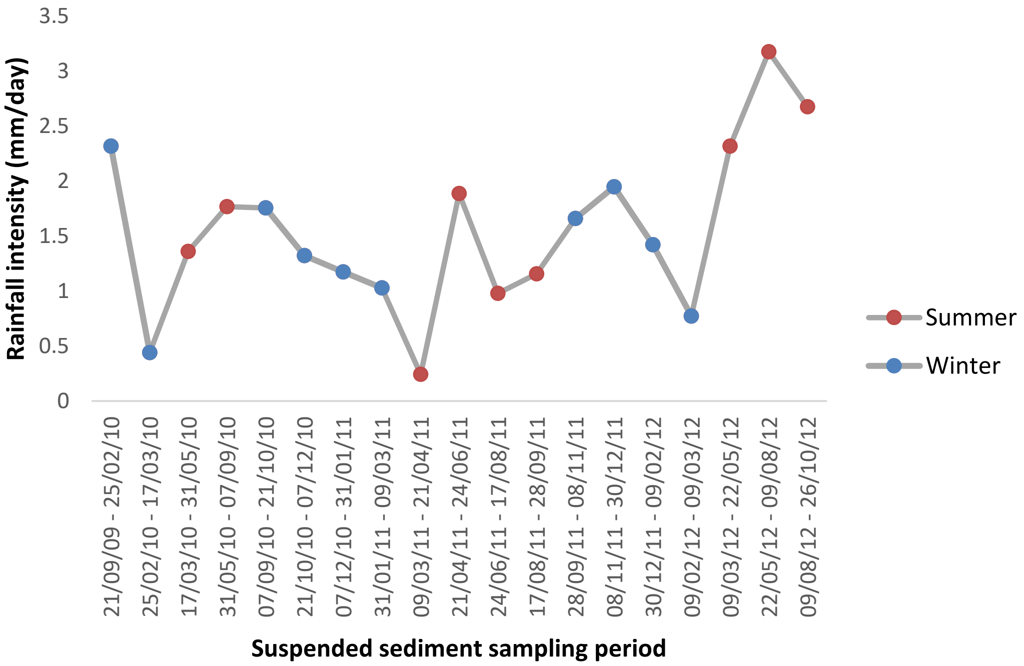

Figure 6.28 Rainfall intensity associated with each sampling period at the Marlbrook Farm monitoring site (*Leominster gauging station, Environment Agency 2013*).

Field reconnaissance identified that steeply incised actively eroding channel banks characterise the sub-catchments located in the upper parts of the Lugg catchment (Figure 6.29). This along with the responsive nature of the channel network, is likely to significantly increase the detachment and entrainment of channel bank material during these high-energy events (Walling *et al.,* 1999b; Owens *et al.,* 2000; Collins 2008). Therefore, the dominance of these sub-catchments is likely to reflect the occurrence of several extreme rainfall events during the 2012 summer season.

Figure 6.29 Examples of steeply incised, easily erodible channel banks in sub-catchments located in the upper parts of the Lugg catchment A) un-named tributary at Treburvaugh and B) Cascob Brook (14th June 2011).

Furthermore, the Glasnant tributary sub-catchment is a major contributor of fine sediment to all monitoring sites. However, it is evident that relative contributions from this particular source area cease after January and March 2011 at the Arrow and Lugg monitoring sites respectively. Stage-rainfall relationships at the Hunton monitoring site identify that there was an extreme flash flood event on 3rd October 2010 following localised heavy rainfall confined to the upper parts of the catchment (Figure 6.30). This event was the greatest over the whole period of study which, as reported by the Stakeholder Advisory Group, was followed by major bank collapses in the catchment. Subsequent contributions estimated from this sub-catchment ranged between 25 and 40% in the sampling period immediately after the event (October-December 2010). Fine sediment was flushed out through the system during this first major flood event of the season, which coincided with the time when particle availability is at a maximum following a dry summer (Lefrançois *et al.,* 2007). This exhausted the sediment supply in the months preceding the event (Steegen *et al*., 2000; Hudson, 2003). For instance, contributions from this source area were estimated to be less than 10%, with as little as 1% at the Broadward monitoring site, for the sampling period succeeding the event (December-January 2011). This is supported by Oeurng *et al*., (2010) who reported that scatter in suspended sediment in the Save catchment, southwestern France, was attributable to the exhaustion of sediment available at the beginning and end of a flood event. Sediment generated from this source area during the high magnitude flood event was routed through the Lugg system in preceding events and stopped contributing to the suspended sediment flux at the Lugg outlet after March 2011 (Appendix 2.5).

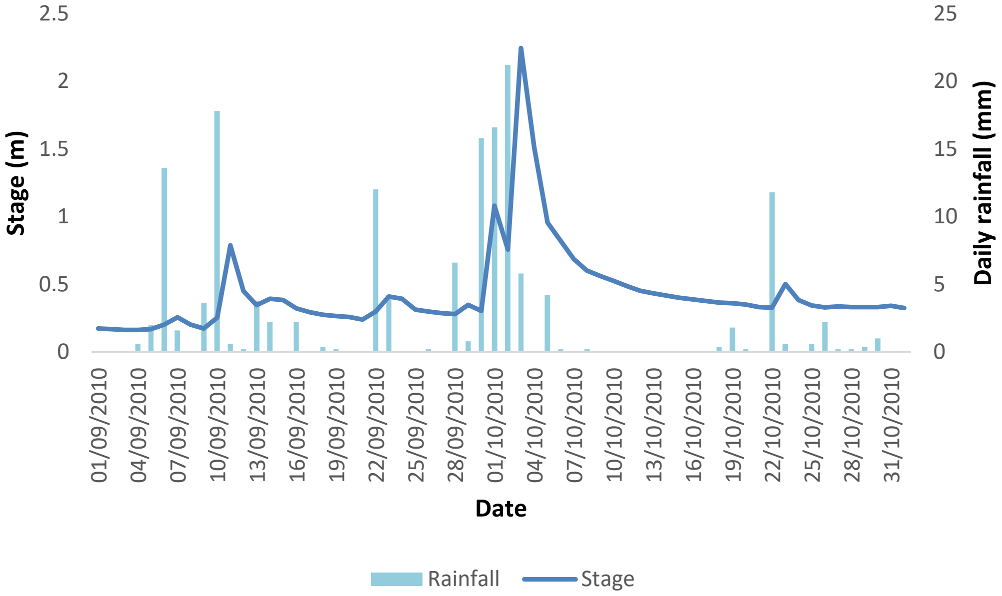

Figure 6.30 Hunton Bridge monitoring site hydrograph for the period September to November 2010 and associated daily rainfall (*Shobdon Airfield gauging station, Met Office 2013*).

In addition to variations in the magnitude and intensity of precipitation, the proximity of tributary sub-catchments relative to individual sink sites is a potential control determining the relative importance of catchment sediment source areas. It is evident from the mixing model outputs that dominant sub-catchments situated close to the monitoring sites contribute high proportions of fine sediment. As a result, sediment mobilised from these sub-catchments is only entrained in the river channel network for a relatively short amount of time before it is routed through the catchment outlet. Therefore, this sediment is less likely to be subjected to conveyance losses such as those associated with overbank deposition (Walling *et al.,* 1999b). Conversely, fine sediment generated from other source areas in the upper parts of the catchment is more likely to be deposited and stored within the channel when velocities are reduced between flood events. For instance, the Honeylake Brook sub-catchment is situated directly upstream of the Broadward monitoring site and is associated with the greatest load-weighted mean fine sediment contribution (19±4%). Sediment mobilised and transported from this source area does not have to travel far through the channel network for dilution with increased flow to have an effect. Given the close proximity of the Honeylake Brook sub-catchment to the Broadward monitoring site, it is possible that sediment mobilised from other tributary sub-catchments further upstream was not transported through the channel network during low energy flow events. Contributions from this tributary sub-catchment are high throughout the 2011 summer season with contributions ranging from 43 to 51% (Appendix 2.2). Although this period was characterised by periods of heavy rainfall, the hydrograph response was limited (Figure 6.31). Walling *et al*. (1999b) reported that contributions from sub-catchments located close to the catchment outlet are likely to predominate during the early part of a flood event, whereas relative contributions from sub-catchments further away are likely to increase during the latter part of a flood event. Therefore, greater energy is required to initiative movement and transport sediment from sub-catchment source areas located further upstream.

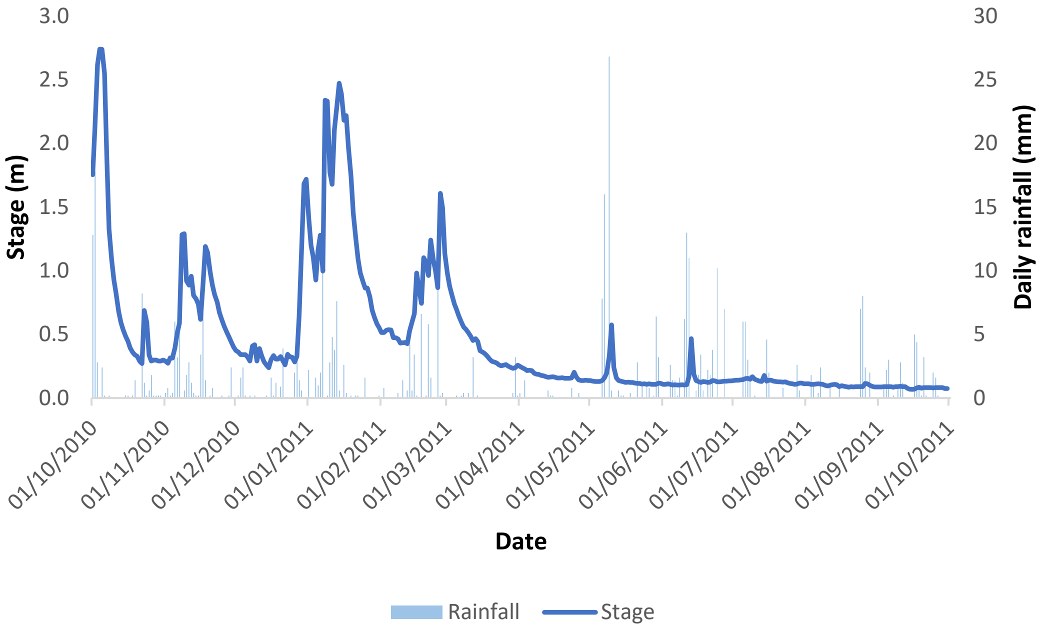

Figure 6.31 Broadward Farm monitoring site hydrograph for the 2010-2011 hydrological year and associated daily rainfall (*Leominster gauging station, Environment Agency 2013*).

The absence of contributions from the Honeylake Brook sub-catchment during this period at monitoring sites located downstream in the Lugg catchment further supports this theory. For example, this sub-catchment contributes less than 1% to the total suspended sediment collected at the Lugwardine monitoring site between May and September 2011 (Appendix 2.5). Therefore, the temporal fluctuations observed here indicate that lower flow, non-event conditions were characterised by contributions from sub-catchments located in close proximity to the sink site.

Similarly, the Little Lugg and the Cheaton Brook sub-catchments are located directly upstream of the Lugwardine and Eaton monitoring sites and are associated with the greatest contributions at each site (11±2 and 23±4% respectively). However, although sediment dilution and inputs from various other sources along the channel network reduced the relative importance of the latter source area, the Cheaton Brook sub-catchment contributes a relatively high proportion of sediment to the two monitoring sites further downstream (Appendix 2.4 – 2.5). This suggests that spatial location of source areas may not independently reflect the variations in sediment contributions.

Temporal variations in fine sediment contributions can also be associated with localised catchment events, which can determine the relative importance of sediment source areas during periods of different flow. This is evident in the Wellington Brook sub-catchment, where a program of in-channel works involving the installation of check weirs backfilled with alluvial gravel occurred throughout 2011 to increase flows and provide suitable salmonid spawning sites (Wye and Usk Foundation). This work coincided with a shift in dominant source areas contributing to the suspended sediment load at the Lugwardine monitoring site (Figure 6.32). For instance, the greatest temporal contribution from this source area was less than 5% prior to this in-channel work, whereas contributions ranged from 18 to 41% between February and September 2011, when these works were being undertaken (Appendix 2.5).

Similarly, the Marl Brook sub-catchment was associated with random periods of high fine sediment contributions which can be attributed to localised catchment events. In general, temporal contributions from this tributary sub-catchment were less than 10 and 15% for the Lugwardine and Marlbrook monitoring sites respectively. However, it is evident that contributions greater than 25% occurred between March and June 2011 at both sink sites (Appendix 2.4 – 2.5). Field reconnaissance demonstrated that high sediment loadings were observed from this sub-catchment in April 2011 (Figure 6.33) which was attributed to a burst water pipe and resulting roadworks close to the channel network.

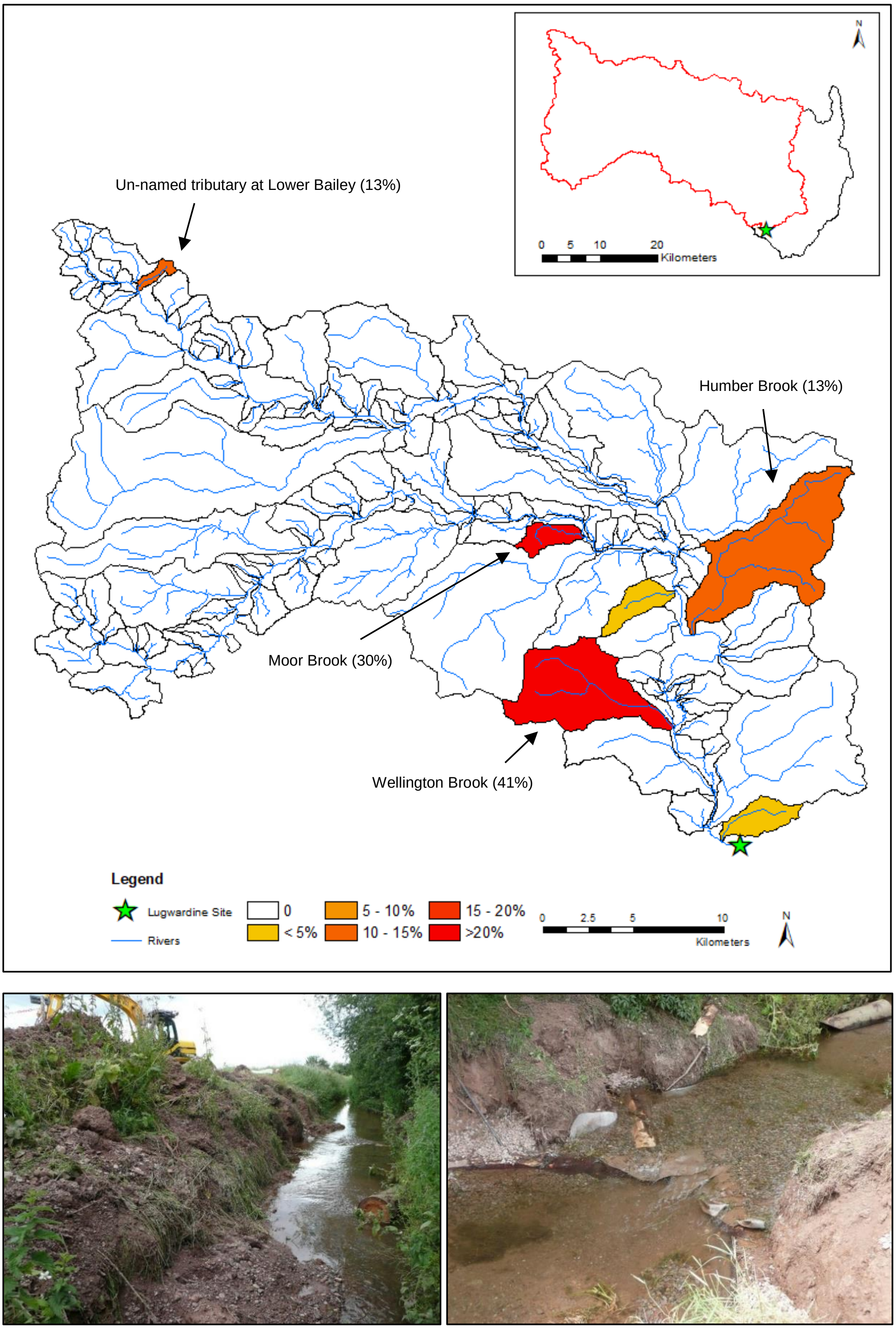

Figure 6.32 Source contribution to the total suspended sediment collected at the Lugwardine monitoring site for the period 17/08/11-28/09/11 and in-channel works in the Wellington Brook sub-catchment.

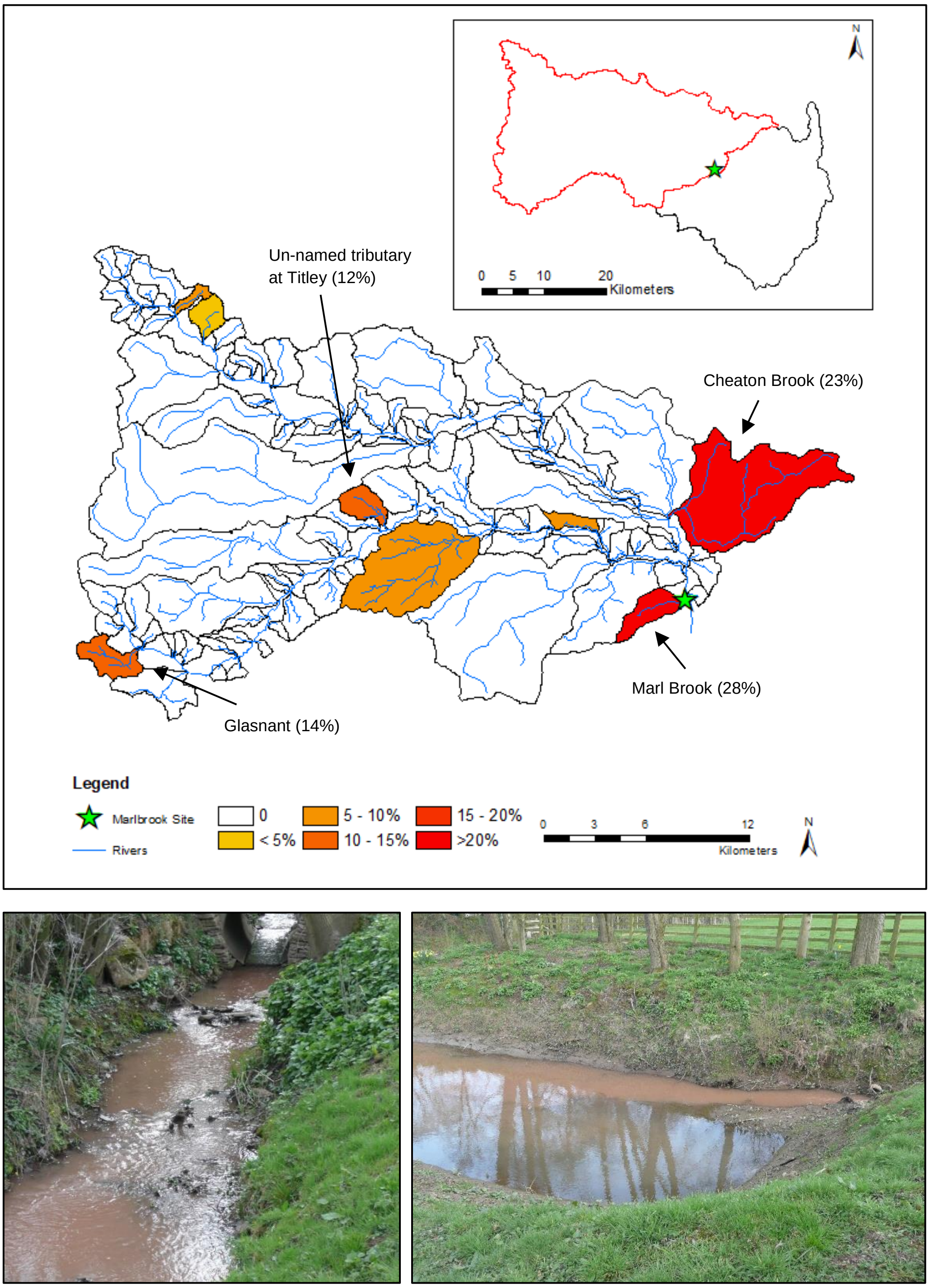

Figure 6.33 Source contribution to the total suspended sediment collected at the Marlbrook monitoring site for the period 09/03/11-21/04/11 and high sediment inputs from the Marl Brook tributary sub-catchment.

The sediment apportionment results from this study can also be put into context with other sediment mobilisation and delivery studies within the Lugg catchment. As a direct response to the episodic high sediment loadings identified by the Environment Agency General Quality Assessment (GQA) network, several projects have been commissioned to investigate fine sediment delivery. For instance, the Rural Sediment Tracing Project was initiated by the Environment Agency in 2009 with the aim of identifying and classifying catchment sources of fine sediment inputs to streams and rivers within 11 priority catchments in rural areas across England. According to the survey undertaken in the lower parts of the Lugg catchment (APEM 2010), the majority of severe fine sediment sources were concentrated in the Stretford Brook sub-catchment. Sources included arable runoff, poaching, runoff from farm tracks and sediment delivery from fords crossing the watercourse. This supports the source apportionment results, which identified this sub-catchment as delivering persistent sediment contributions to key sites over different flow events. In addition, the Rural Sediment Tracing Report identified severe fine sediment sources in the Humber and Bodenham Brook sub-catchments. Although the load-weighted mean contribution from the latter sub-catchment was less than 5% at the Lugwardine monitoring site, contributions greater than 25% were evident during individual flow events during the winter season. In contrast, the mixing model estimated that contributions from the Humber Brook were limited, although contributions greater than 10% were identified during two individual sampling periods in the summer season (Appendix 2.5).

Wet weather sediment mobilisation and delivery studies in the Lugg catchment (Environment Agency, 2006; McEwen *et al*., 2011) also identified spatial variability in fine suspended sediment loadings in several sub-catchments. The 2006 study to verify previous SIMCAT and PSYCHIC modelling work in the catchment identified the Cheaton, Stretford and Honeylake Brooks plus the Little Lugg as sub-catchments particularly at risk of severe fine sediment runoff. This supports the source apportionment results, which identified these sub-catchments as persistently delivering sediment to key sites within the Lugg catchment. The source apportionment results established that temporal contributions from the Cheaton Brook sub-catchment were estimated to be as high as 52 and 64% at the Marlbrook and Lugwardine monitoring sites respectively, whilst contributions greater than 40% were estimated from the Honeylake Brook sub-catchment at the Broadward monitoring site (Appendix 2.3 – 2.5). In addition, the Ridgemoor Brook was identified to be particularly poor, whilst elevated sediment loads following rainfall were observed in the Curl

Brook sub-catchment in the sediment mobilisation and delivery study. The source apportionment results concurred with this, with load-weighted mean sediment contributions from the Curl Brook ranging from 8 to 15% and temporal contributions from the Ridgemoor Brook estimated to be greater than 70% during two individual events.

Furthermore, the 2011 wet weather sediment mobilisation and delivery study identified the Humber, Bodenham and Honeylake Brooks as sub-catchments with the greatest turbidity and suspended sediment concentrations. High loadings in the latter catchment were generally attributable to major sediment runoff from road and farm track surfaces directly entering the watercourses upstream of recently ploughed arable fields (McEwen *et al.,* 2011). This observation supports the source apportionment results which indicated that this sub-catchment contributes greater amounts of fine sediment during the winter months at the Broadward monitoring site, when degradation and damage associated with the use of heavy machinery associated with harvesting activities is at a maximum (Figure 6.13).

6.5 Summary

This chapter has presented the catchment scale source apportionment results and the subsequent identification of the most dominant tributary sub-catchments that persistently deliver fine sediment to sink sites within the Lugg catchment. The sediment fingerprinting technique using geochemical tracing properties has identified the Cheaton, Ridgemoor, Curl, Stretford, Honeylake and Moor Brooks plus the Little Lugg as the predominant spatial sources of suspended sediment collected at the monitoring sites. In addition, sub-catchments located in the upper parts of the catchment have been identified as dominant sources of fine sediment. These include the un-named tributaries at Treburvaugh and Lucton and the Glasnant sub-catchment.

The dominance and variations in relative source contributions from specific tributary sub-catchments reflects a combination of factors controlling sediment mobilisation and delivery. These factors include variations in catchment area and the spatial distribution of source areas; elevation and slope across the study catchment; the underlying soil type of individual source areas; land use activities and land cover; inter-storm variations in the magnitude and intensity of precipitation; proximity of source areas to sampling points; and localised catchment events. The relative merit of these factors has been considered and put into context with field reconnaissance and frequent discussions with the Stakeholder Advisory Group.

This catchment-wide investigation has helped verify previous work in the catchment that has identified sub-catchments at risk of severe fine sediment runoff and has assisted in strengthening evidence of the sediment problem in the Lugg catchment. It has also provided an evidence base to aid catchment management, identifying priority areas for which mitigation measures should be targeted to tackle the fine sediment problem. Furthermore, it has identified dominant source areas which can subsequently be focused on by deploying the sediment source fingerprinting procedure at the sub-catchment level. This will help to verify the controls that determine the relative importance of catchment source areas and to further aid catchment management by enabling the implementation of mitigation measures in an effective targeted approach. The following two chapters detail the sub-catchment scale source apportionment results.

CHAPTER 7
SUB-CATCHMENT SCALE SEDIMENT FINGERPRINTING STATISTICAL RESULTS

7.1 Introduction

This chapter presents the results from the refined sediment source fingerprinting procedure applied to suspended sediment samples collected at the four sub-catchment outlets within the Lugg catchment.

7.2 Fingerprint Property Range Tests

In order to identify properties suitable for inclusion in the optimum composite fingerprint, it was important that a property concentration range test (see Chapter 4) was conducted on the suspended sediment and source material. As suspended sediment samples were collected over different flow conditions, it was essential to treat each sample independently to allow greater statistical verification. It was therefore only those properties that did not fall within the range of source material concentrations for any of the suspended sediment samples that were considered to fail this particular analysis. Tables 7.1 - 7.4 display the fingerprint property range test results for each sub-catchment. It was evident that out of the available suite of 20 properties, only one property (Na) failed the concentration range test for the Cheaton Brook sub-catchment (Table 7.1). Three properties failed this test for the Ridgemoor Brook (Na, Mn, Sr), Curl Brook (Na, Sr, Ba) and Moor Brook (Na, Ca, Sr) sub-catchments (Tables 7.2 – 7.4). Consequently, these properties are not incorporated within the following statistical procedure. For the remaining properties, several, if not all, individual suspended sediment concentrations fell within the concentration ranges of source material.

Of the 19 properties that passed the property range concentration test in the Cheaton Brook sub-catchment, three properties had suspended sediment concentration ranges which fell completely within the concentration ranges for the source material, one property had suspended sediment concentration ranges which overlapped the minimum concentration source value and 15 properties had suspended sediment ranges which overlapped the maximum concentration source value (Table 7.1). Nine of the 17 properties which passed this analysis within the Ridgemoor Brook sub-catchment had suspended sediment concentration ranges that fell entirely within the source material ranges, with eight suspended sediment properties overlapping the maximum concentration source value (Table 7.2). Within the Curl Brook sub-catchment, of the 17 properties that passed this test four had suspended sediment concentration ranges that fell fully within the concentration ranges for the source material, seven properties contained suspended sediment concentration ranges that overlapped the minimum concentration source value and six suspended sediment properties overlapped the maximum concentration source value (Table 7.3). Of the 17 properties that passed the concentration range test in the Moor Brook sub-catchment, one property had suspended sediment concentration ranges that fell entirely within the source material concentration ranges. Eight properties had suspended sediment ranges which overlapped the minimum source concentration value and eight suspended sediment properties overlapped the maximum concentration source value (Table 7.4).

Table 7.1 Cheaton Brook sub-catchment property range test results for (a) individual suspended sediment samples and (b) all suspended sediment samples.

(a)

	Fingerprint properties																			
Suspended sediment samples	**Na**	**Mg**	**Al**	**K**	**Ca**	**V**	**Cr**	**Mn**	**Fe**	**Co**	**Ni**	**Cu**	**Zn**	**As**	**Sr**	**Mo**	**Ag**	**Cd**	**Ba**	**Pb**
29 Mar – 17 May 12		X	X	X	X	X	X	X	X	X	X	X	X	X		X		X	X	X
17 May – 14 Jun 12			X			X	X		X	X	X	X	X	X				X		X
14 Jun – 06 Jul 12		X	X		X	X			X		X		X	X		X	X	X	X	X
06 – 13 Jul 12		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
13 Jul – 08 Aug 12			X			X	X		X			X	X	X		X	X	X		X
08 Aug – 04 Sep 12			X			X						X		X			X	X		X
04 Sep – 01 Oct 12			X	X	X	X	X		X	X		X	X	X	X		X	X	X	X
01 – 24 Oct 12					X	X		X					X	X				X	X	X
24 Oct – 13 Nov 12			X			X		X	X	X		X	X	X				X		

X = Suspended sediment concentration values within the range of source concentration values

Highlighted properties disregarded

(b)

Suspended sediment range within source range	V, As, Cd
Suspended sediment range overlaps source minimum value	Pb
Suspended sediment range overlaps source maximum value	Mg, Al, K, Ca, Cr, Mn, Fe, Co, Ni, Cu, Zn, Sr, Mo, Ag, Ba
Suspended sediment range outside source range	Na*

Suspended sediment range = Minimum to maximum property concentration values
Source range = Minimum mean - standard deviation to maximum mean + standard deviation of mean source group property values

* Property disregarded from further analysis

Table 7.2 Ridgemoor Brook sub-catchment property range test results for (a) individual suspended sediment samples and (b) all suspended sediment samples.

(a)

	Fingerprint properties																			
Suspended sediment samples	**Na**	**Mg**	**Al**	**K**	**Ca**	**V**	**Cr**	**Mn**	**Fe**	**Co**	**Ni**	**Cu**	**Zn**	**As**	**Sr**	**Mo**	**Ag**	**Cd**	**Ba**	**Pb**
29 Mar – 17 May 12		X	X	X		X	X		X	X	X	X		X		X		X		X
17 May – 14 Jun 12		X	X	X		X	X		X	X	X	X	X	X		X	X	X		X
14 Jun – 13 Jul 12		X	X	X	X	X	X		X	X	X	X	X	X		X	X	X	X	X
13 Jul – 08 Aug 12			X	X		X	X		X	X	X	X	X	X		X	X	X		X
08 Aug – 04 Sep 12		X	X	X		X	X		X	X	X	X		X		X	X	X		X
04 Sep – 01 Oct 12			X	X		X	X		X	X	X	X	X	X				X		X
01 – 24 Oct 12			X			X			X	X	X	X	X	X				X	X	X
24 Oct – 13 Nov 12			X			X	X		X	X	X	X	X	X		X	X	X		X

X = Suspended sediment concentration values within the range of source concentration values

Highlighted properties disregarded

(b)

Suspended sediment range within source range	Al, V, Fe, Co, Ni, Cu, As, Cd, Pb
Suspended sediment range overlaps source minimum value	
Suspended sediment range overlaps source maximum value	Mg, K, Ca, Cr, Zn, Mo, Ag, Ba
Suspended sediment range outside source range	Na*, Mn*, Sr*

Suspended sediment range = Minimum to maximum property concentration values
Source range = Minimum mean - standard deviation to maximum mean + standard deviation of mean source group property values

* Property disregarded from further analysis

Table 7.3 Curl Brook sub-catchment property range test results for (a) individual suspended sediment samples and (b) all suspended sediment samples.

(a)

	Fingerprint properties																			
Suspended sediment samples	**Na**	**Mg**	**Al**	**K**	**Ca**	**V**	**Cr**	**Mn**	**Fe**	**Co**	**Ni**	**Cu**	**Zn**	**As**	**Sr**	**Mo**	**Ag**	**Cd**	**Ba**	**Pb**
22 Mar – 17 May 12		X	X	X	X	X	X	X			X		X	X		X	X			X
17 May – 14 Jun 12								X					X	X		X	X	X		
14 Jun – 06 Jul 12		X	X	X	X	X		X	X	X	X		X	X		X	X	X		X
06 – 13 Jul 12							X	X			X		X	X		X	X	X		
13 Jul – 08 Aug 12			X	X		X	X	X	X	X	X		X	X		X	X			X
08 Aug – 04 Sep 12				X			X	X			X	X	X	X		X	X	X		
04 Sep – 01 Oct 12		X		X	X		X	X			X	X	X	X		X	X	X		
01 – 24 Oct 12			X			X		X	X	X	X	X	X	X			X			
24 Oct – 13 Nov 12							X	X					X	X		X	X	X		

X = Suspended sediment concentration values within the range of source concentration values

Highlighted properties disregarded

(b)

Suspended sediment range within source range	Mn, Zn, As, Ag
Suspended sediment range overlaps source minimum value	Al, V, Fe, Co, Ni, Cu, Pb
Suspended sediment range overlaps source maximum value	Mg, K, Ca, Cr, Mo, Cd
Suspended sediment range outside source range	Na*, Sr*, Ba*

Suspended sediment range = Minimum to maximum property concentration values
Source range = Minimum mean - standard deviation to maximum mean + standard deviation of mean source group property values

* Property disregarded from further analysis

Table 7.4 Moor Brook sub-catchment property range test results for (a) individual suspended sediment samples and (b) all suspended sediment samples.

(a)

	Fingerprint properties																			
Suspended sediment samples	**Na**	**Mg**	**Al**	**K**	**Ca**	**V**	**Cr**	**Mn**	**Fe**	**Co**	**Ni**	**Cu**	**Zn**	**As**	**Sr**	**Mo**	**Ag**	**Cd**	**Ba**	**Pb**
22 Mar – 17 May 12		X		X		X			X	X	X	X		X		X	X		X	X
17 May – 14 Jun 12														X		X	X	X		
14 Jun – 06 Jul 12		X	X			X	X	X	X	X	X	X	X	X		X	X	X		X
06 – 13 Jul 12		X					X	X			X	X	X	X		X		X		
13 Jul – 08 Aug 12							X					X	X	X		X	X	X		
08 Aug – 04 Sep 12		X										X		X		X	X	X		
04 Sep – 01 Oct 12		X	X	X		X	X		X	X	X	X	X	X		X	X	X	X	X
01 – 24 Oct 12			X			X	X	X	X	X	X	X	X	X		X	X	X	X	
24 Oct – 13 Nov 12							X	X					X			X	X	X		

X = Suspended sediment concentration values within the range of source concentration values

Highlighted properties disregarded

(b)

Suspended sediment range within source range	Mo
Suspended sediment range overlaps source minimum value	Al, V, Fe, Co, Ni, Cu, As, Pb
Suspended sediment range overlaps source maximum value	Mg, K, Cr, Mn, Zn, Ag, Cd, Ba
Suspended sediment range outside source range	Na*, Ca*, Sr*

Suspended sediment range = Minimum to maximum property concentration values
Source range = Minimum mean - standard deviation to maximum mean + standard deviation of mean source group property values

* Property disregarded from further analysis

If the method proposed by Haley (2010) was followed explicitly, then it was only the properties whose suspended sediment concentrations fell completely within the range of the corresponding source material concentrations that were deemed to pass this analysis. Therefore, only a limited number of properties for each sub-catchment would have been included in subsequent analyses, which would prove insufficient for sediment source discrimination. This restricted number of properties could be the result of collecting suspended sediment samples over a range of different flow conditions. This coupled with the fact that Haley's method was developed for floodplain sediment cores, rather than suspended sediment samples, indicated that for this study it was more appropriate to relax the constraints to determine whether a property was successful. Consequently, properties were deemed to pass this particular analysis if any of the individual suspended sediment concentrations fell within the corresponding source range. However, properties where only a few individual suspended sediment concentrations fell within the source range, notably Sr for the Cheaton Brook sub-catchment, Ca and Ba for Ridgemoor Brook and K for the Moor Brook sub-catchment, had to be treated with caution. The successful properties which met the range test requirements were subsequently utilised in the source discrimination analysis.

7.3 Sediment Source Discrimination

7.3.1 Kruskal-Wallis H-Test

Those geochemical properties that passed the property concentration range test were then subjected to a Kruskal-Wallis *H*-test (see Chapter 5, section 5.4.1). For each sub-catchment this test assessed the ability of individual properties to distinguish between specific source types. Properties that that fell below the critical *H*-value indicated insufficient statistical distinction and as a result, were removed from any further consideration as feasible fingerprint properties.

Tables 7.5 – 7.8 present the results of the Kruskal-Wallis *H*-test for discriminating the specific source types within each sub-catchment. In the case of the Cheaton Brook sub-catchment 18 of 19 fingerprint properties yielded test statistics in excess of the critical *H*-value (9.49). The only property to fail the first stage of the property selection process was Mn, which generated *H*- and p-values of 6.929 and 0.140 respectively (Table 7.5). The corresponding results for the Ridgemoor Brook sub-catchment show 2 of 15 elements (Mg and Ba) failed the Kruskal-Wallis *H*-test, generating test results below the critical *H*-value (7.81) (Table 7.6). For the Curl Brook sub-catchment, 2 of 15 elements (K and Mn) failed the Kruskal-Wall *H*-test within this sub-catchment, yielding test statistics below the critical *H*-value (9.49). Moor Brook displayed the greatest failure rate, with 7 of 17 elements (K, Mn, Zn, As, Mo, Ag and Pb) producing test statistics below the critical *H*-value (7.81).

Table 7.5 Cheaton Brook sub-catchment Kruskal-Wallis *H*-test results for the source material fingerprint property dataset.

Fingerprint property	*H*-value	p-value
Mg	37.570	0.000
Al	36.182	0.000
K	19.976	0.002
Ca	26.125	0.000
V	31.700	0.000
Cr	26.297	0.000
Mn	6.929	0.140*
Fe	28.966	0.000
Co	29.044	0.000
Ni	33.153	0.000
Cu	16.940	0.002
Zn	30.300	0.000
As	36.899	0.000
Sr	24.408	0.000
Mo	36.073	0.000
Ag	34.002	0.000
Cd	31.097	0.000
Ba	31.805	0.000
Pb	26.257	0.000
* statistically insignificant critical *H*-value = 9.49 critical *p*-value = 0.05		

Table 7.6 Ridgemoor Brook sub-catchment Kruskal-Wallis *H*-test results for the source material fingerprint property dataset.

Fingerprint property	*H*-value	p-value
Mg	5.233	0.155*
Al	11.437	0.010
K	16.352	0.001
Ca	16.800	0.001
V	9.471	0.024
Cr	11.138	0.011
Fe	9.195	0.027
Co	8.196	0.042
Ni	9.215	0.027
Cu	11.350	0.010
Zn	17.648	0.001
As	9.515	0.023
Mo	28.073	0.000
Ag	13.268	0.004
Cd	19.433	0.000
Ba	5.031	0.170*
Pb	28.507	0.000
* statistically insignificant critical *H*-value = 7.81 critical *p*-value = 0.05		

Table 7.7 Curl Brook sub-catchment Kruskal-Wallis *H*-test results for the source material fingerprint property dataset.

Fingerprint property	*H*-value	p-value
Mg	16.076	0.003
Al	33.743	0.000
K	5.383	0.250*
Ca	25.190	0.000
V	15.983	0.003
Cr	29.411	0.000
Mn	5.972	0.201*
Fe	12.862	0.012
Co	11.670	0.020
Ni	17.666	0.001
Cu	10.292	0.036
Zn	35.872	0.000
As	16.495	0.002
Mo	26.003	0.000
Ag	18.530	0.001
Cd	27.109	0.000
Pb	29.372	0.000
* statistically insignificant critical *H*-value = 9.49 critical *p*-value = 0.05		

Table 7.8 Moor Brook sub-catchment Kruskal-Wallis *H*-test results for the source material fingerprint property dataset.

Fingerprint property	*H*-value	p-value
Mg	9.089	0.028
Al	16.283	0.001
K	4.326	0.228*
V	14.494	0.002
Cr	15.202	0.002
Mn	4.534	0.209*
Fe	14.757	0.002
Co	10.007	0.019
Ni	14.378	0.002
Cu	13.801	0.003
Zn	4.141	0.247*
As	1.113	0.774*
Mo	5.210	0.157*
Ag	2.783	0.426*
Cd	7.854	0.049
Ba	12.381	0.006
Pb	1.556	0.669*
* statistically insignificant critical *H*-value = 7.81 critical *p*-value = 0.05		

7.3.2 Discriminant Function Analysis

Discriminant Function Analysis (DFA) was utilised to test the ability of the properties passing the Kruskal-Wallis *H*-test to classify potential source material into correct groups, and to identify the set of tracer properties that afforded optimum discrimination within each sub-catchment. Both simultaneous entry and stepwise selection DFA methods were applied to ensure an acceptable level of discrimination was generated. Only the properties that were able to provide maximum discrimination were used in the subsequent sediment source apportionment.

Cheaton Brook

Table 7.9 presents the simultaneous entry DFA results for the Cheaton Brook sub-catchment. Using this method, all 18 properties that passed the Kruskal-Wallis *H*-test were selected for the composite fingerprint. As a result, 73.2% of the source type samples were correctly classified and a Wilks' lambda value of

0.009 was produced. It is evident that channel bank and woodland sources offered the greatest discrimination with 95.7% and 90% of the samples correctly classified respectively (Table 7.10). Ten out of the 14 farm track samples were correctly classified (71.4%), with one sample being incorrectly predicted as belonging to each of the other source categories. However, arable and pasture sources were poorly discriminated, with only 42.9% and 61.9% of the samples correctly classified respectively. Of the arable samples that were incorrectly classified, 28.6% were predicted as belonging to the pasture source group and 14.3% were predicted to be channel bank and farm track samples. Four out of the eight misclassified pasture samples were incorrectly predicted to be channel bank samples, with two samples predicted as belonging to the arable source group and two incorrectly predicted to be farm track samples.

Table 7.9 Simultaneous entry DFA results for the Cheaton Brook sub-catchment.

Fingerprint properties	Source type samples classified correctly (%)	Wilks' lambda
Mg, Al, K, Ca, V, Cr, Fe, Co, Ni, Cu, Zn, As, Sr, Mo, Ag, Cd, Ba, Pb	73.2	0.009

Table 7.10 The predicted sample group compared against the actual group membership for each source type within the Cheaton Brook sub-catchment following simultaneous entry DFA.

	Source Type	Predicted Group Membership					Total
		Arable	Pasture	Channel banks	Woodland	Farm tracks	
No.	Arable	6	4	2	0	2	14
	Pasture	2	13	4	0	2	21
	Channel banks	1	0	22	0	0	23
	Woodland	0	1	0	9	0	10
	Farm tracks	1	1	1	1	10	14
%	Arable	42.9	28.6	14.3	0	14.3	100
	Pasture	9.5	61.9	19	0	9.5	100
	Channel banks	4.3	0	95.7	0	0	100
	Woodland	0	10	0	90	0	100
	Farm tracks	7.1	7.1	7.1	7.1	71.4	100

The composite fingerprint selected using simultaneous entry DFA offered overall discrimination of 73.2%. However, owing to the relatively poor discrimination evident for the arable and pasture source categories, stepwise selection DFA was applied to the tracer properties to determine if improved discrimination could be obtained for the Cheaton Brook sub-catchment (Table 7.11). Stepwise DFA is based on the minimisation of Wilks' lambda; it maximises discrimination between source groups, whilst minimising the combination of tracer properties to provide the optimum composite fingerprint.

Table 7.11 Stepwise selection DFA results, identifying the optimum composite fingerprint for discriminating individual sediment source types in the Cheaton Brook sub-catchment.

Step	Fingerprint properties	Cumulative source type samples classified correctly (%)	Wilks' lambda
1	Mg	32.9	0.479
2	Cr	53.7	0.157
3	Mo	72	0.086
4	Ba	75.6	0.055
5	V	75.6	0.045
6	Al	75.6	0.037
7	Fe	75.6	0.032
8	Pb	74.4	0.028
9	Ag	76.8	0.023

The optimum composite fingerprint for the Cheaton Brook sub-catchment contained a combination of nine properties that discriminated 76.8% of the source type samples correctly (Table 7.11), as opposed to the 73.2% offered using the simultaneous entry DFA procedure. The Wilks' lambda value improved from 0.479 to 0.023. It is evident that the inclusion of V, Al and Fe did not enhance the percentage of source samples correctly classified. However, the inclusion of these properties improved the Wilks lambda value from 0.055 to 0.032, which demonstrates that the level of discrimination is assessed on the percentage of source samples classified correctly along with the Wilks' lambda value. It is also apparent that the inclusion of Pb in the eighth step slightly reduced the percentage of source samples correctly classified from 75.6% to 74.4%. However, the inclusion of this property not only improved the Wilks' lambda value from 0.032 to 0.028, but the subsequent addition of Ag in the final step further enhanced source discrimination.

Table 7.12 demonstrates that the stepwise selection procedure yielded greater source group discrimination for three out of the five source groups, compared to the simultaneous entry method. For example, greater discrimination was evident for the pasture and farm track sources, with 76.2% and 78.6% of the samples correctly classified respectively. Of the pasture samples that were incorrectly classified, 9.5% were predicted as belonging to the arable source group, with 4.8% and 9.5% correspondingly predicted as channel bank and farm track samples (Table 7.12). Although greater discrimination was afforded by stepwise rather than simultaneous DFA for the arable source, it is evident that this particular group was the most poorly discriminated with only 50% of the samples correctly classified. Of the incorrectly classified samples, 35.7% were predicted as belonging to the pasture source group; this could reflect the influence of the rotation of agricultural land-use within this particular sub-catchment and the wider Lugg catchment. Some arable samples may have been collected from sites which had previously been used for pasture and may therefore still retain similar geochemical properties (Haley, 2010; Burke, 2011).

It is evident that woodland and channel bank sources still offered the greatest discrimination using the stepwise selection procedure, with 90% and 87% of the samples correctly classified, respectively (Table 7.12). However, there is greater misclassification associated with the channel bank samples with 8.7% of the incorrectly classified samples predicted as belonging to the arable source group and 4.3% predicted to be pasture sources. This could reflect the influence of the surface horizon material, resembling similar geochemical property characteristics to the surrounding land-use, being mixed with material collected from the lower horizons of the exposed channel bank sections (Burke, 2011). In such instances, channel bank samples are incorrectly classified as topsoil samples, demonstrating the difficultly of obtaining greater levels of discrimination.

Table 7.12 The predicted sample group compared against the actual group membership for each source type within the Cheaton Brook sub-catchment following the stepwise selection DFA procedure.

	Source Type	**Predicted Group Membership**					**Total**
		Arable	Pasture	Channel banks	Woodland	Farm tracks	
No.	Arable	7	5	2	0	0	14
	Pasture	2	16	1	0	2	21
	Channel banks	2	1	20	0	0	23
	Woodland	0	1	0	9	0	10
	Farm tracks	1	0	1	1	11	14
%	Arable	50	35.7	14.3	0	0	100
	Pasture	9.5	76.2	4.8	0	9.5	100
	Channel banks	8.7	4.3	87	0	0	100
	Woodland	0	10	0	90	0	100
	Farm tracks	7.1	0	7.1	7.1	78.6	100

Statistical classification of the source material samples is illustrated in Appendix 3.1 (based on Collins and Walling 2007). The scatter plots display the sample distribution around the group centroids (i.e. the mean values of the discriminant score for individual groups) at each step throughout the stepwise classification procedure. In the early stages of the DFA it is evident that considerable overlap exists between the samples representing the arable, pasture, channel bank and farm track source types. Although the woodland samples appear as a group distinct from the other source types, the individual samples show a relatively higher level of over dispersion from the group centroid. The selection of an additional fingerprint property with each stage of the DFA process improves the discrimination between source categories until the final fingerprint is produced, where there is greater separation between individual source group centroids and tighter clustering of individual samples. This is particularly visible for the channel bank, woodland and farm track source groups, with minimal overlapping from other source samples. However, the scatter and overlapping apparent between the arable and pasture source groups is indicative of the difficulty of obtaining greater levels of discrimination for groups that may encompass similar geochemical property characteristics, for example, agricultural land that experience rotation between pasture and arable land-uses.

Greater discriminatory power was offered by the stepwise selection procedure; the inclusion of weak or redundant properties in the simultaneous entry DFA method reduced overall discrimination and increased the number of misclassifications. Nevertheless, owing to the particularly poor discrimination apparent between the arable and pasture sources in the Cheaton Brook sub-catchment, these source groups were amalgamated to form a larger ‘agricultural land’ category to assess whether enhanced discrimination could be obtained (Burke, 2011). The previously adopted sediment source discrimination statistical procedure was therefore replicated. Although this merged data did not change the number of properties surviving the Kruskal-Wallis *H*-test, nor the only property (Mn) that failed this elimination process, it was evident that the *H*-values for each property were lower, indicating a reduction in inter-group contrasts. The stepwise DFA improved separation, with an optimum composite fingerprint containing seven properties that correctly classified 81.9% of the source type samples, as opposed to the initial 76.8%. However, it is apparent that the associated Wilks’ lambda deteriorated from the original value of 0.023 to 0.042 (Table 7.13).

Table 7.13 Stepwise selection DFA results, identifying the optimum composite fingerprint for discriminating individual sediment source types in the Cheaton Brook sub-catchment, with arable and pasture sources amalgamated.

Step	Fingerprint properties	Cumulative source type samples classified correctly (%)	Wilks’ lambda
1	Mg	49.4	0.556
2	Cr	57.8	0.201
3	Mo	79.5	0.111
4	Ba	79.5	0.072
5	V	81.9	0.059
6	Fe	84.3	0.049
7	Al	81.9	0.042

The amalgamation of the arable and pasture samples offered greater source group discrimination for the channel bank and woodland source groups, with 87% and 100% of the samples correctly classified respectively (Table 7.14). The agricultural land source group correctly classified 77.8% of the samples, with 13.9% incorrectly predicted as channel bank samples. However, there was greater misclassification associated with the farm track samples, with 21.4% incorrectly predicted as belonging to the agricultural land source group. This could reflect the difficulty of discriminating between two different sources that resemble similar geochemical property characteristics.

Table 7.14 The predicted sample group compared against the actual group membership for each source type within the Cheaton Brook sub-catchment following the stepwise DFA procedure, with arable and pasture sources amalgamated.

	Source Type	**Predicted Group Membership**				**Total**
		Agricultural	Channel banks	Woodland	Farm tracks	
No.	Agricultural	28	5	1	2	36
	Channel banks	3	20	0	0	23
	Woodland	0	0	10	0	10
	Farm tracks	3	0	1	10	14
%	Agricultural	77.8	13.9	2.8	5.6	100
	Channel banks	13	87	0	0	100
	Woodland	0	0	100	0	100
	Farm tracks	21.4	0	7.1	71.4	100

Figure 7.1 illustrates the classification of the source material samples provided by the final optimum composite fingerprint. The woodland samples are distinctively grouped and display a slightly tighter clustering around the group centroid, as opposed to the previous stepwise selection procedure. However, it is evident that the farm track samples are more dispersed from the group centroid and therefore amplify the overlapping with other source groups. Whilst the amalgamation of the arable and pasture groups prevented the poor discrimination associated between the two main land use types in the Cheaton Brook sub-catchment, it failed to further reduce the scatter observed with the farm track and channel bank groups. Therefore, although the overall percentage of source types classified correctly increased to 81.9%, the amalgamation of the arable and pasture source groups did not dramatically improve source discrimination.

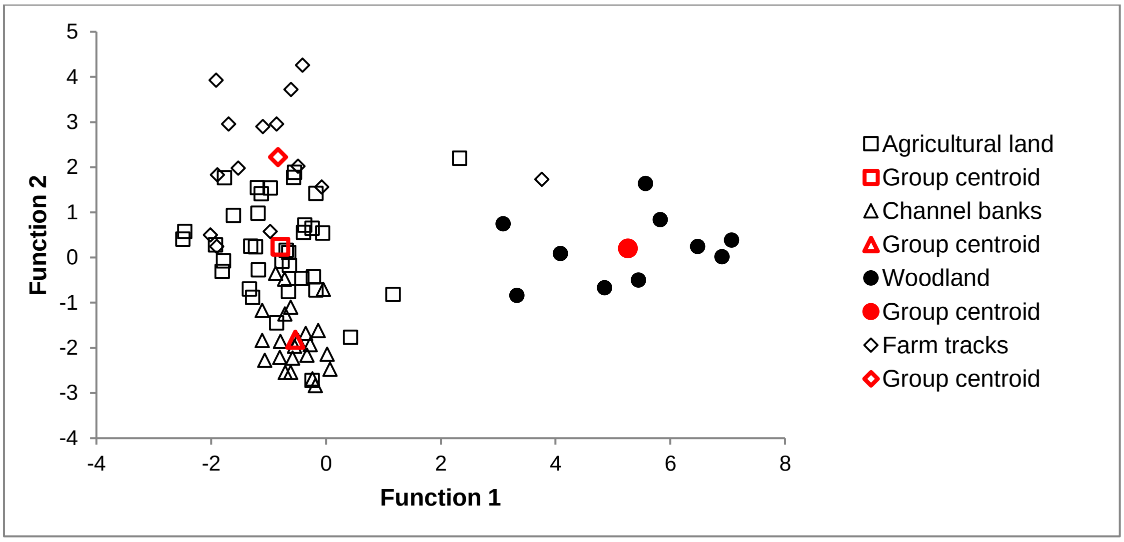

Figure 7.1 Sample distribution around group centroids using stepwise DFA for the Cheaton Brook sub-catchment, with arable and pasture sources amalgamated.

Approximately 90% of the land use in the Cheaton Brook sub-catchment is agricultural comprising of either arable or pasture. Owing to the large area of land covered by the two source groups, it would be difficult for catchment managers to accurately identify areas where mitigation measures are required to reduce fine sediment problems within the catchment. Through discussions with the Stakeholder Advisory Group (see Chapter 3) discrimination between the two major land use types was considered more valuable from a management perspective. As a result, the optimum composite fingerprint that was identified through the stepwise selection procedure, comprising of nine properties (Mg, Cr, Mo, Ba, V, Al, Fe, Pb and Ag) and producing a Wilks' lambda value of 0.023 (Table 7.11), was used in the subsequent sediment source ascription phase for the Cheaton Brook sub-catchment.

Ridgemoor Brook

In the case of the Ridgemoor Brook sub-catchment, all 17 properties which passed the Kruskal-Wallis *H*-test were selected for the composite fingerprint following simultaneous entry DFA (Table 7.15). This fingerprint correctly classified 70.5% of the source type samples and produced a Wilks' lambda value of 0.056. Table 6.16 presents the sample group prediction compared to the actual group membership for the four source groups within the Ridgemoor

Brook sub-catchment. It is apparent that the farm track source group was the most poorly discriminated, with only 40% of the samples correctly classified. 30% of the misclassified farm track samples were predicted as belonging to the pasture source group and 20% were predicted to be arable samples. The arable source group offered the greatest discrimination with 83.3% of the samples correctly classified, with 11.1% incorrectly classified as pasture samples. Pasture and channel bank samples were correctly discriminated in 75% and 69.2% of cases respectively. Four (20%) of the misclassified pasture source samples were incorrectly predicted as belonging to the channel bank source group, and 15.4% of the channel bank samples were incorrectly predicted to be arable samples.

Table 7.15 Simultaneous entry DFA results for the Ridgemoor Brook sub-catchment.

Fingerprint properties	Source type samples classified correctly (%)	Wilks' lambda
Mg, Al, K, Ca, V, Cr, Fe, Co, Ni, Cu, Zn, As, Mo, Ag, Cd, Ba, Pb	70.5	0.056

Table 7.16 The predicted sample group compared against the actual group membership for each source type within the Ridgemoor Brook sub-catchment following simultaneous entry DFA.

	Source Type	Predicted Group Membership				Total
		Arable	Pasture	Channel banks	Farm tracks	
No.	Arable	15	2	1	0	18
	Pasture	1	15	4	0	20
	Channel banks	2	1	9	1	13
	Farm tracks	2	3	1	4	10
%	Arable	83.3	11.1	5.6	0	100
	Pasture	5	75	20	0	100
	Channel banks	15.4	7.7	69.2	7.7	100
	Farm tracks	20	30	10	40	100

Owing to the overall discrimination of 70.5% offered by the selected composite fingerprint and the poor discrimination for the farm track source group, stepwise selection DFA was applied to the tracer properties to ascertain if improved discrimination could be obtained for the Ridgemoor Brook sub-catchment (Table

7.17). It is evident that this method offered an optimum composite fingerprint containing a combination of eight properties with an enhanced discrimination of 75.4% and a Wilks' lambda value improving from 0.603 to 0.090. The inclusion of Zn in the final step slightly reduced the percentage of source samples correctly classified from 77% to 75.4%. However, the inclusion of this property improved the Wilks' lambda value from 0.108 to 0.090, demonstrating the requirement to minimise the lambda statistic, whilst maximising the percentage of source samples correctly classified.

Table 7.17 Stepwise selection DFA results, identifying the optimum composite fingerprint for discriminating individual sediment source types in the Ridgemoor Brook sub-catchment.

Step	Fingerprint property	Cumulative source type samples classified correctly (%)	Wilks' lambda
1	Mo	52.5	0.603
2	Fe	60.7	0.447
3	Cr	67.2	0.303
4	V	70.5	0.232
5	Al	68.9	0.169
6	K	77.0	0.128
7	Pb	77.0	0.108
8	Zn	75.4	0.090

The stepwise selection procedure utilised in the Ridgemoor Brook sub-catchment, improved correct classification across three out of the four source groups, compared to the simultaneous entry method. For example, greater discrimination was evident for the pasture and channel bank sources, with 80% and 76.9% of the samples correctly classified respectively (Table 7.18). Of the pasture samples, 10% were incorrectly classified as belonging to both the arable and channel bank source groups. Two (15.4%) of the misclassified channel bank samples were incorrectly predicted to be arable samples, whereas one sample was predicted as belonging to the farm track source group. Although the farm track source group discrimination greatly improved from the simultaneous entry procedure, it is clear that this particular source group was still the most poorly discriminated, with 70% of the samples correctly classified (Table 7.18). 20% of the farm track samples were incorrectly predicted as belonging to the pasture source group, which could reflect the difficulty of classifying farm tracks that were located within or close to pasture fields, and as a result consist of similar geochemical property characteristics (Figure 7.2).

Figure 7.2 Examples of farm tracks located within pasture fields in the Ridgemoor Brook sub-catchment, reflecting the relatively poor discrimination for this particular source group (28th - 30th August 2012).

However, there is greater misclassification associated with the arable source samples using the stepwise selection procedure, with 27.8% of the samples incorrectly classified (Table 7.18). 16.7% of the incorrectly classified samples were predicted as belonging to the channel bank source group, which could reflect the influence of the channel bank topsoil, exposed to arable land-use, being mixed with material collected from the lower horizons of exposed channel banks.

Table 7.18 The predicted sample group compared against the actual group membership for each source type within the Ridgemoor Brook sub-catchment following the stepwise selection DFA procedure.

	Source Type	**Predicted Group Membership**				**Total**
		Arable	Pasture	Channel banks	Farm tracks	
No.	Arable	13	1	3	1	18
	Pasture	2	16	2	0	20
	Channel banks	2	0	10	1	13
	Farm tracks	0	2	1	7	10
%	Arable	72.2	5.6	16.7	5.6	100
	Pasture	10	80	10	0	100
	Channel banks	15.4	0	76.9	7.7	100
	Farm tracks	0	20	10	70	100

The classification of the source material samples provided by the optimum composite fingerprint is shown in Appendix 3.2, which displays the sample distribution around the four group centroids following stepwise selection DFA. It is evident that poor discrimination is offered in the early stages of the DFA, as considerable overlap exists between all the samples. This is particularly noticeable for the pasture and farm track source groups, where the individual samples are dispersed from the group centroids, which are situated in very close proximity to one another. This reflects the difficulty of classifying farm tracks that were located within or close to pasture fields (Figure 7.2). The selection of an additional fingerprint property with each stage of the DFA process improves the discrimination between source categories until the final fingerprint is produced, where there is greater separation between source group centroids and tighter clustering of individual samples. However, this is not the case for the arable and channel bank source groups, as the samples overlapped the corresponding group centroid, which is indicative of the difficulty in obtaining greater levels of discrimination for subsurface sources that may encompass similar geochemical property characteristics to the overlying surface land-use.

Therefore, greater discriminatory power was offered by the stepwise selection procedure, where 75.4% of the source samples were correctly classified. It was evident that the inclusion of weak or redundant properties in the simultaneous entry DFA method reduced overall discrimination and increased the number of misclassifications. As a result, the optimum composite fingerprint which comprised of eight properties (Mo, Fe, Cr, V, Al, K, Pb and Zn) and produced a Wilks’ lambda value of 0.090 was used in the subsequent sediment source ascription phase for the Ridgemoor Brook sub-catchment.

Curl Brook

For the Curl Brook sub-catchment, simultaneous entry DFA utilised the 17 properties that passed the Kruskal-Wallis *H*-test to form a composite fingerprint which correctly classified 73.7% of the source type samples and produced a Wilks’ lambda value of 0.018 (Table 7.19). It is evident from Table 7.20 that channel bank and pasture samples offered the greatest discrimination with

83.3% and 81.3% of the samples correctly classified respectively. Fourteen out of the 19 arable samples were correctly classified (73.7%), with three samples incorrectly predicted as belonging to the woodland source group. However, farm track and woodland sources were poorly discriminated, with only 58.3% and 63.6% of the samples correctly classified respectively. Of the farm track samples that were poorly discriminated, 25% were predicted as belonging to the woodland source group and 8.3% were predicted to be arable and channel bank samples. Two out of the four misclassified woodland samples were incorrectly predicted to be arable samples, with two samples also predicted as belonging to the channel bank source group.

Table 7.19 Simultaneous entry DFA results for the Curl Brook sub-catchment.

Fingerprint properties	Source type samples classified correctly (%)	Wilks' lambda
Mg, Al, K, Ca, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Mo, Ag, Cd, Pb	73.7%	0.018

Although the simultaneous DFA-based fingerprint gave an overall discrimination of 73.7%, relatively poor discrimination was evident for the farm track and woodland source categories. Therefore, stepwise selection DFA was applied to the tracer properties to ascertain if improved discrimination could be obtained for the Curl Brook sub-catchment.

Table 7.20 The predicted sample group compared against the actual group membership for each source type within the Curl Brook sub-catchment following simultaneous entry DFA.

	Source Type	Predicted Group Membership					Total
		Arable	Pasture	Channel banks	Woodland	Farm tracks	
No.	Arable	14	1	0	3	1	19
	Pasture	2	13	0	1	0	16
	Channel banks	1	1	15	1	0	18
	Woodland	2	0	2	7	0	11
	Farm tracks	1	0	1	3	7	12
%	Arable	73.7	5.3	0	15.8	5.3	100
	Pasture	12.5	81.3	0	6.3	0	100
	Channel banks	5.6	5.6	83.3	5.6	0	100
	Woodland	18.2	0	18.2	63.6	0	100
	Farm tracks	8.3	0	8.3	25	58.3	100

The optimum composite fingerprint selected using this stepwise selection method contained a combination of eight properties with an enhanced discrimination of 78.9% and a Wilks' lambda value improving from 0.570 and 0.043 (Table 7.21). The inclusion of Cd in the final step failed to further enhance the percentage of source samples correctly classified offered by the addition of Cr in the previous step. However, the inclusion of this property improved the Wilks' lambda value from 0.051 to 0.043.

Table 7.21 Stepwise selection DFA results, identifying the optimum composite fingerprint for discriminating individual sediment source types in the Curl Brook sub-catchment.

Step	Fingerprint property	Cumulative source type samples classified correctly (%)	Wilks' lambda
1	Al	32.9	0.570
2	V	52.6	0.308
3	Zn	60.5	0.174
4	Ni	65.8	0.111
5	Mg	71.1	0.085
6	Mo	76.3	0.061
7	Cr	78.9	0.051
8	Cd	78.9	0.043

By utilising the stepwise selection procedure for the Curl Brook sub-catchment, correct classification was enhanced across four out of the five source groups. Greater discrimination was evident for the farm track, pasture and arable sources, with 75%, 87.5% and 78.9% of the samples correctly classified respectively (Table 7.22). Of the three farm track samples that were incorrectly classified, one sample was each predicted as belonging to the woodland, channel bank and arable source group. Only two pasture samples were misclassified, with one sample predicted as arable and one sample predicted as woodland. 10.5% of the arable samples were incorrectly predicted to be woodland samples, which could reflect the difficultly of classifying small areas of woodland located in the vicinity of more dominant arable land, visible in this particular sub-catchment. In such instances, both land-use types could consist of similar geochemical property characteristics. Although the woodland source group offered greater discrimination as opposed to the simultaneous entry method, it is evident that this particular source group was the most poorly discriminated, with 72.7% of the samples correctly classified (Table 7.22). All of the misclassified woodland samples were predicted as belonging to the channel bank source group.

Table 7.22 The predicted sample group compared against the actual group membership for each source type within the Curl Brook sub-catchment following the stepwise selection DFA procedure.

	Source Type	**Predicted Group Membership**					**Total**
		Arable	**Pasture**	**Channel banks**	**Woodland**	**Farm tracks**	
No.	Arable	15	1	0	2	1	19
	Pasture	1	14	0	1	0	16
	Channel banks	1	1	14	2	0	18
	Woodland	0	0	3	8	0	11
	Farm tracks	1	0	1	1	9	12
%	Arable	78.9	5.3	0	10.5	5.3	100
	Pasture	6.3	87.5	0	6.3	0	100
	Channel banks	5.6	5.6	77.8	11.1	0	100
	Woodland	0	0	27.3	72.7	0	100
	Farm tracks	8.3	0	8.3	8.3	75	100

However, there is greater misclassification associated with the channel bank samples using the stepwise selection procedure, with 22.2% of the samples incorrectly classified (Table 7.22). Two of the four channel bank samples which were incorrectly classified were predicted as belonging to the woodland source group. Excessive channel bank erosion was observed in woodland areas, especially in the upper parts of the sub-catchment. In such instances, the difficulty of obtaining higher levels of discrimination could have been reflected by the influence of the surface horizon material, resembling similar geochemical property characteristics to the surrounding woodland, being mixed with material collected from the lower horizons of the exposed channel bank sections. This could therefore explain the 11.1% and 27.3% of sample misclassifications for the channel bank and woodland source groups respectively.

The classification of the source material samples provided by the optimum composite fingerprint is shown in Appendix 3.3. The sample distribution around the five group centroids is displayed in the form of scatter plots at each step throughout the stepwise selection procedure. It is evident that poor discrimination is offered in the early stages of the DFA, as considerable overlap exists between all of the samples. This is particularly noticeable for the arable, pasture and channel bank sources, where the corresponding group centroids are situated in very close proximity to one another. The selection of an additional fingerprint property with each stage of the DFA process improves the discrimination between source categories until the final fingerprint is produced. Although some overlapping is apparent between the samples, this fingerprint offers greater separation between the individual source group centroids and tighter clustering of the corresponding samples. This is particularly visible for the woodland source group, where individual samples are tightly clustered around the group centroid but overlap the pasture and channel bank source samples. This is indicative of the difficulty in obtaining greater levels of discrimination for groups that may encompass similar geochemical properties. Nevertheless, it is clear that distinct groupings are present.

Therefore, it was considered that the optimum composite fingerprint comprising of eight properties (Al, V, Zn, Ni, Mg, Mo, Cr and Cd) which was identified through the stepwise selection procedure, offered greater discriminatory power, as 78.9% of the source samples were classified correctly and a Wilks' lambda value of 0.043 was produced. As a result, this composite fingerprint was used in the subsequent sediment source ascription phase for the Curl Brook sub-catchment, as the inclusion of redundant properties in the simultaneous entry method reduced overall discrimination and increased the number of misclassifications.

Moor Brook

In the case of the Moor Brook sub-catchment, simultaneous entry DFA selected the 17 properties which passed the Kruskal-Wallis *H*-test to form a composite fingerprint which correctly classified 71.4% of the source type samples and produced a Wilks' lambda value of 0.014 (Table 7.23). The sample group prediction compared to the actual group membership for the five source groups within the Moor Brook sub-catchment is presented in Table 7.24. It is evident that arable and farm track sources offered the greatest discrimination with 100% and 83.3% of the samples correctly classified respectively. The misclassified farm track samples were predicted as belonging to the arable source group. However, the channel bank source group was poorly discriminated, with only

50% of the samples correctly classified. Three out of the four misclassified channel bank samples were incorrectly predicted to be pasture samples, with one sample predicted as belonging to the farm track source group (Table 7.24). Poor discrimination was also apparent for the pasture source group, with only 57.1% of the samples correctly classified. 28.6% of the pasture samples were incorrectly classified as belonging to the farm track source group and 14.3% were predicted to be channel bank samples.

Table 7.23 Simultaneous entry DFA results for the Moor Brook sub-catchment.

Fingerprint properties	Source type samples classified correctly (%)	Wilks' lambda
Mg, Al, K, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Mo, Ag, Cd, Ba, Pb	71.4%	0.014

Table 7.24 The predicted sample group compared against the actual group membership for each source type within the Moor Brook sub-catchment following simultaneous entry DFA.

	Source Type	Predicted Group Membership				Total
		Arable	Pasture	Channel banks	Farm tracks	
No.	Arable	7	0	0	0	7
	Pasture	0	4	1	2	7
	Channel banks	0	3	4	1	8
	Farm tracks	1	0	0	5	6
%	Arable	100	0	0	0	100
	Pasture	0	57.1	14.3	28.6	100
	Channel banks	0	37.5	50	12.5	100
	Farm tracks	16.7	0	0	83.3	100

Owing to the overall discrimination of 71.4% offered by the selected composite fingerprint and the poor discrimination evident for the channel bank and pasture source groups, stepwise selection DFA was applied to the tracer properties. This aimed to establish if enhanced discrimination could be obtained for the Moor Brook sub-catchment. Following this process an optimum composite fingerprint was produced, which contained a combination of seven properties with a greater discrimination of 85.7% and a Wilks' lambda value improving from 0.431 to 0.028 (Table 7.25). The inclusion of Ni in the fifth step slightly reduced the percentage of source samples correctly classified from 71.4% to

64.3%. However, the inclusion of this property not only improved the Wilks' lambda value from 0.126 to 0.085, but the subsequent addition of Mg and V in the sixth and seventh step further enhanced source discrimination.

Table 7.25 Stepwise selection DFA results, identifying the optimum composite fingerprint for discriminating individual sediment source types in the Moor Brook sub-catchment.

Step	Fingerprint property	Cumulative source type samples classified correctly (%)	Wilks' lambda
1	Al	50.0	0.431
2	Cu	60.7	0.239
3	Ba	64.3	0.168
4	Cd	71.4	0.126
5	Ni	64.3	0.085
6	Mg	82.1	0.040
7	V	85.7	0.028

By utilising the stepwise selection procedure for the Moor Brook sub-catchment, correct classification was enhanced across two out of the four source groups. For example, greater discrimination was evident for the previously poorly discriminated channel bank and pasture source groups, with 100% and 85.7% of the samples correctly classified respectively (Table 7.26). The only misclassified pasture sample was predicted as belonging to the farm track source group. As was apparent with the simultaneous entry method, the optimum composite fingerprint correctly classified all the arable samples. However, there is greater misclassification associated with the farm track source samples using the stepwise selection procedure, with only 50% of the samples correctly classified (Table 7.26). All of the misclassified farm track samples were incorrectly predicted as belonging to the arable source group, which could reflect the difficulty of classifying farm tracks that were located within or close to arable fields (Figure 7.3). As a result, these particular samples could consist of similar geochemical property characteristics.

Table 7.26 The predicted sample group compared against the actual group membership for each source type within the Moor Brook sub-catchment following the stepwise selection DFA procedure.

	Source Type	**Predicted Group Membership**				**Total**
		Arable	**Pasture**	**Channel banks**	**Farm tracks**	
No.	Arable	7	0	0	0	7
	Pasture	0	6	0	1	7
	Channel banks	0	0	8	0	8
	Farm tracks	3	0	0	3	6
%	Arable	100	0	0	0	100
	Pasture	0	85.7	0	14.3	100
	Channel banks	0	0	100	0	100
	Farm tracks	50	0	0	50	100

Figure 7.3 Example showing a farm track adjacent to arable fields connected with field entrances in the Moor Brook sub-catchment, reflecting the poor discrimination offered for this particular source group (19th September 2012).

The classification of the source material samples provided by the optimum composite fingerprint is shown in Appendix 3.4, which displays the sample distribution around the four group centroids following stepwise selection DFA. It is evident that poor discrimination is offered in the early stages of the DFA as overlap exists between all of the samples without any clustering around the corresponding group centroids. This is particularly noticeable for the arable, channel bank and farm track sources, where the individual samples are dispersed from the group centroids, which are situated in close proximity to one another. The selection of an additional fingerprint property with each stage of the DFA process improves the discrimination between source categories until the final fingerprint is produced, where there is greater separation between source group centroids and tighter clustering of individual samples. This is particularly visible for the pasture and channel bank source samples, which display distinctive groupings. However, although there is minimal scatter and overlapping apparent between the arable and farm track source samples, the group centroids are situated fairly close to one another. This reflects the difficulty in obtaining greater levels of discrimination for groups that may include samples displaying similar geochemical property characteristics from another group.

Therefore, the optimum composite fingerprint identified by the stepwise selection procedure comprised of seven properties (Al, Cu, Ba, Cd, Ni, Mg and V), and offered enhanced discriminatory power, which correctly classified 85.7% of the source samples and produced a Wilks' lambda value of 0.028. This composite fingerprint was used in the subsequent sediment source ascription phase for the Moor Brook sub-catchment, as the inclusion of redundant properties in the simultaneous entry DFA method reduced overall discrimination and increased the number of misclassifications. However, the recommended case-to-variable ratio of 3:1, (see Chapter 5), was exceeded given the small number of source samples (cases) and relatively high number of fingerprint properties (variables). Owing to the small size of the Moor Brook sub-catchment only 28 samples were attained (Figure 3.17d), creating a case-to-variable ratio of 1.65:1. It was not feasible to obtain a greater number of source samples, as pseudoreplication would have occurred and there is no sound rationale for reducing the number of variables used in the DFA process. As a result, the DFA outputs for this particular sub-catchment were interpreted with caution.

Summary of Provenance Discrimination

The source discrimination achieved by stepwise DFA ranged from 75.4% (Ridgemoor Brook) to 85.7% (Moor Brook). Although the discriminatory power was considered sufficient for the sediment source ascription phase, it was evident that the overall sediment provenance discrimination for each sub-catchment was generally below that reported in several previous studies (Table 7.27). For example, many studies utilising the stepwise selection procedure correctly classified between 90% and 100% of the source samples (Collins *et al*., 1997a; Russell *et al.,* 2001; Collins and Walling, 2002; 2007; Collins, 2008; Walling *et al.,* 2008; Collins *et al*., 2009; 2010b; 2010c; 2012b; 2014; Pulley *et al.,* 2017). There could be a number of important factors limiting the discriminating power of the final composite fingerprint for each sub-catchment. These include (i) the failure to incorporate all potential sources throughout field reconnaissance in the particular catchment; (ii) the exclusion of fingerprint properties from a wide range of different subsets which are influenced by differing environmental controls (Collins *et al*., 1998; Walling *et al.,* 2002; 2008) and the limited number of fingerprint properties used in the discrimination process; and (iii) the poor performance of individual fingerprint properties owing to specific environmental factors, for example, the underlying geology (Collins and Walling 2002).

The failure to incorporate all potential source types into the sediment fingerprinting approach could limit the discrimination offered by the final composite fingerprint. Although, the research design incorporated the main source types based on the prevailing land-use and previous studies in the available literature (see Chapter 3), it is apparent that other sources of fine sediment could contribute to the suspended sediment loads. Russell *et al*. (2001) conducted a sediment fingerprinting study in a small sub-catchment of the Lugg and demonstrated the importance of field drains and hopyards as sources of fine sediment, contributing 55% and 12% respectively to the suspended sediment load. Road surfaces have also been established as significant sources of fine sediment. Gruszowski *et al.* (2003) reported that 30% of the suspended sediment collected in the Herefordshire River Leadon was derived from, or transported via, roads. Both these studies achieved enhanced discriminatory power, with 87.4 – 89.4% and 83.9% of source samples correctly classified respectively (Table 7.27). These values were greater than the discrimination achieved in the Cheaton Brook (Table 7.11), Ridgemoor Brook (Table 7.17) and Curl Brook (Table 7.21) sub-catchments. The relatively low discrimination achieved in the sub-catchments could in part be attributable to the failure to incorporate all potential source types into the sediment fingerprinting design. However, it is evident that the discrimination offered by the composite fingerprint in the Moor Brook sub-catchment (Table 7.25) was within range of the discrimination values reported in the two previous studies, albeit below the values attained in other studies (Table 7.27). This suggests that additional factors to miscounting all potential sediment sources could limit the discriminating power of the final composite fingerprint.

The discrimination offered by the final composite fingerprint for each sub-catchment could also be restricted through the failure to incorporate fingerprint properties from a range of different subsets and by the limited number of variables used in the discrimination process. Although it has been acknowledged that composite fingerprints comprising several individual properties from a particular property subset can afford robust discrimination, it has been accepted that enhanced discriminatory power can be obtained from properties drawn from a combination of different subsets (Collins *et al*., 1998; Collins and Walling 2002). Most of the studies identified in Table 7.27 which reported enhanced discriminatory power, identified composite fingerprints comprising diagnostic properties from a combination of geochemical, mineral-magnetic, radionuclide and organic elements. For example, Pulley *et al*. (2017) used a mixture of mineral magnetic, geochemical and colour signatures as potential sediment source tracers which correctly classified 100% of the source type samples, whereas Walling *et al*. (2006) used radiometric, geochemical and organic elements to provide a discriminatory power of between 88.3 and 97.5% in the Thames catchment. However, it is evident that some studies achieved source discrimination in excess of 90%, whilst only using one diagnostic subset. In such instances, an extensive number of geochemical properties (greater than 40) with differing environmental behaviour have been utilised to ensure that reliable sediment provenance discrimination was afforded (e.g. Collins 2008; Collins *et al*., 2010b; 2010c; 2012a; 2012b). Therefore, the number of variables used in the source discrimination phase could have an influence on the discrimination offered by the final composite fingerprint. From Table 7.27 it is evident that the two studies that offered the lowest source discrimination used less than 25 individual properties (e.g. Owens *et al*., 2000; Gruszowski *et al.,* 2003). Nevertheless, other studies using a limited number of individual properties (ranging from 20 to 27) have achieved source discrimination in excess of 90% (e.g. Collins *et al*., 1997a; 1997b; Heywood, 2002; Walling *et al*., 2008). This suggests that the number of different properties from one or multiple diagnostic subsets is not the only control limiting the source discrimination.

The poor performance of individual properties could also reflect the homogeneous geology and pedologic characteristics of the Lugg catchment (Russell *et al.,* 2001; Collins and Walling 2002). According to Collins *et al.* (1998) contrasting geological and pedological characteristics generate distinctive fingerprints with greater discriminatory power. Geochemical property characteristics are likely to be similar where the geology and overlaying soil is homogeneous across a catchment thereby limiting the discrimination of different source groups. As identified in Table 7.27 previous studies within the Lugg catchment and neighbouring River Leadon, both of which encompass similar homogeneous geology characteristics, achieved limited sediment provenance discrimination. For example, Collins *et al*. (2013) reported discriminatory power of 79-85% on the River Arrow using geochemical properties. This is comparable to the discrimination achieved in this study for the two sub-catchments located in the Arrow catchment (78.9 and 85.7% for the Curl and Moor Brook respectively). In addition, discrimination achieved in studies by Russell *et al.* (2001) and Gruszowski *et al*. (2003), using a mixture of mineral magnetic, environmental radionuclides and geochemical properties, was 87.4-89.4% and 83.9% in the Lugg and Leadon catchments respectively. Nevertheless, enhanced discriminatory power is achieved in the Lugg catchment when using organic tracer properties. When utilising these tracers, the discrimination offered by the final composite fingerprint in the River Arrow increased to 91-95% (Collins *et al.,* 2013a), whereas in the Lugg Collins *et al.* (2014) reported discriminatory power of 95%. This suggests that geochemical tracer properties alone are unlikely to provide the greatest discrimination in catchments with homogeneous geology and pedology. Therefore, the relatively low discriminatory power of the composite fingerprints in this study's four sub-catchments could reflect the nature of the geology and soil type of the Lugg catchment.

An additional factor to consider relates to the method of DFA classification used in previous studies. It is unclear from several previous studies identified in Table

7.27 whether the discriminatory power was generated from the original DFA classification or the cross-validation procedure. As discussed in Chapter 5, the cross-validation procedure generates a less biased estimate of classification accuracy and therefore produces a more reliable presentation of discriminatory power. However, the original classification technique usually generates a superior outcome compared to the cross-validated classification procedure. The differences in the discriminatory power of the composite fingerprints from the four sub-catchments and the previous studies could therefore reflect the two different classification procedures. For instance, the discrimination asserted in the four sub-catchments, which ranged from 75.4% (Ridgemoor Brook) to 85.7% (Moor Brook) was the output of cross-validated DFA classification. However, it is evident that enhanced discrimination, ranging from 81.7% (Cheaton Brook) to 96.4% (Moor Brook) was associated with the original classification procedure. This suggests that if the DFA classification was based on this method, the source discrimination achieved by the four sub-catchments would be similar to that reported in previous studies, providing these studies conveyed discriminatory power based on this procedure. This is particularly apparent when comparing with the discriminatory power of the composite fingerprints achieved in the research conducted by Haley (2010), where original classifications were utilised to achieve source discrimination ranging from 81.7% to 87.4%. Using the same DFA classification method, these values are below the source discrimination achieved in the four sub-catchments in this study. It was therefore considered that the discrimination offered in this research is analogous with the discriminatory power achieved by other studies.

The relatively low provenance discrimination offered by the composite fingerprints in this study is therefore likely to reflect a combination of the important factors limiting discriminating power. Although enhanced discriminatory power has been achieved in previous studies (Table 7.27), it is apparent that similarly low discriminatory power has been reported (e.g. Owens *et al*., 2000; Russell *et al*., 2001; Gruszwoski *et al*., 2003; Collins *et al.,* 2013a). This indicates that the discriminatory power offered by the final composite fingerprint for the four sub-catchments in this study was sufficient for the sediment ascription phase.

Table 7.27 Discrimination offered by previous studies using the sediment fingerprinting approach to identify sources of fine sediment in UK catchments.

Catchment	Sub-catchment / river	Source type samples classified correctly (%)	Number of variables used in analysis	Study
Avon	River Avon	95.1	20	Heywood (2002)
	River Nadder	93.4	25	Walling *et al*. (2008)
	River Sem	100	49	Collins (2008)
	River Till	100	49	Collins (2008)
	Chitterne Brook	95.8	49	Collins (2008)
Axe	Upper Axe	100	46	Collins *et al.* (2012b)
	Temple Brook	96.7	46	Collins *et al.* (2012b)
	River Synderford	100	46	Collins *et al.* (2012b)
	Blackwater River	100	46	Collins *et al.* (2012b)
	Kit Brook	100	46	Collins *et al.* (2012b)
	River Yarty	100	46	Collins *et al.* (2012b)
	River Coly	96.7	46	Collins *et al.* (2012b)
Exe	River Exe	100	26	Collins *et al.* (1997a)
	River Barle	100	36	Collins & Walling (2002)
	River Dart	100	27	Collins *et al.* (1997c)
	River Lowman	100	26	Collins *et al.* (1997a)
	River Bathern	100	26	Collins *et al.* (1997a)
Frome and Piddle	River Frome	100	46	Collins & Walling (2007)
	River Piddle	95.5	46	Collins & Walling (2007)
	South House	100	47	Collins *et al.* (2010c)
	Little Puddle	100	47	Collins *et al.* (2010c)
	Briantspuddle	91.9	47	Collins *et al.* (2010c)
Lugg	Belmont	87.4	31	Russell *et al.* (2001)
	Jubilee	89.4	31	Russell *et al.* (2001)
	River Arrow	91-95	38	Collins *et al.* (2013)
	River Arrow	79-85	46	Collins *et al*. (2013)
	River Lugg	95	39	Collins *et al*. (2014)
Nene	River Nene	100	36	Pulley *et al.* (2017)
Severn	Upper Severn	100	27	Collins *et al*. (1997b)
	Plynlimon	100	36	Collins & Walling (2002)
	River Vyrnwy	100	36	Collins & Walling (2002)
	River Tern	100	36	Collins & Walling (2002)
	River Rhiw	100	26	Collins *et al.* (1997a)
	River Perry	100	26	Collins *et al.* (1997a)
	River Leadon	83.9	23	Gruszowski *et al*. (2003)
Somerset Levels	River Brue	91.8	45	Collins *et al*. (2010b)
	River Cary	98.5	45	Collins *et al*. (2010b)
	Halse Water	100	45	Collins *et al*. (2010b)
	River Isle	95.4	45	Collins *et al*. (2010b)
	River Tone	93.5	45	Collins *et al*. (2010b)
	Upper Parrett	93.3	45	Collins *et al*. (2010b)
	River Yeo	95.4	45	Collins *et al*. (2010b)
Test	River Blackwater	100	39	Collins *et al.* (2013)
Thames	River Lambourn	88.3	48	Walling *et al.* (2006)
	River Pang	97.5	48	Walling *et al.* (2006)
	River Kennet	98.7-100	46	Collins *et al*. (2012a)
Trent (Smisby)	Lower Smisby	93.7	31	Russell *et al.* (2001)
	New Cliftonthorpe	93.7	31	Russell *et al.* (2001)
Tweed	River Tweed	76.2	24	Owens *et al.* (2000)

7.4 Particle Size Effects

Owing to the site-specific relationship between particle size and the concentration of geochemical properties (Chapter 5), it was necessary to consider the differences in particle size composition of the suspended sediment samples and source material for each sub-catchment to enable direct comparison (Walling *et al.,* 2002). It was also essential to take into account any significant correlations between particle size and geochemical concentrations for each sub-catchment, which may require a correction factor.

7.4.1 Particle Size Composition

Figures 7.4 – 7.7 compare the mean particle size composition of the suspended sediment and the source material collected from each sub-catchment, along with the associated SSA of the < 1 mm fraction. It is evident that the suspended sediment particle size distributions are generally finer than the corresponding catchment source material. As a consequence, the SSA values for the suspended sediment samples are usually greater than the source material. This could indicate that selective mobilisation and subsequent delivery processes of the finer material from the source areas occur during rainfall events. This is most prominent in the Cheaton Brook sub-catchment (Figure 7.4), where there are significant differences between the mean suspended sediment particle size and that of the source material. The suspended sediment is characterised by a silt-clay ratio of 7.93, a d_{50} of 10.83 µm and a SSA of 1.27 $m^2 g^{-1}$, whilst the corresponding values for the source material are of 7.8, 21.93 µm and 1.04 $m^2 g^{-1}$ respectively. Similarly, the mean suspended sediment for the Ridgemoor Brook sub-catchment (Figure 7.5) is characterised by a silt-clay ratio of 10.14, a d_{50} of 9.74 µm and a SSA of 1.19 $m^2 g^{-1}$, compared with mean source material values of 7.76, 14.28 µm and 1.19 $m^2 g^{-1}$. However, it is apparent that the enrichment of fine material in the suspended sediment is limited to the > 3 µm fraction, below which the source material is marginally finer than the suspended sediment. Therefore, it is evident that there are no significant differences between the mean suspended sediment particle size and that of the source material in this sub-catchment.

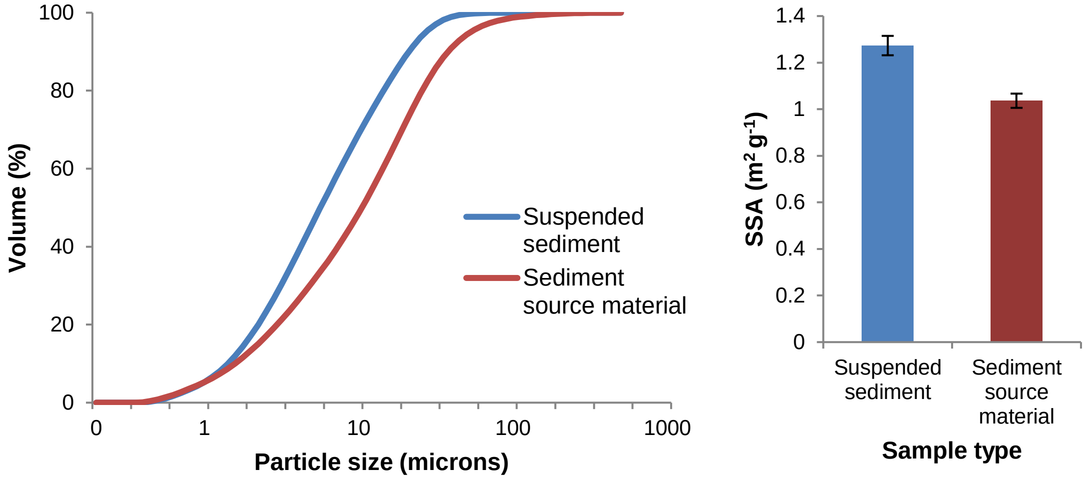

Figure 7.4 Comparison of the mean particle size composition and SSA values (with associated standard error) for the suspended sediment and source material samples for the Cheaton Brook sub-catchment.

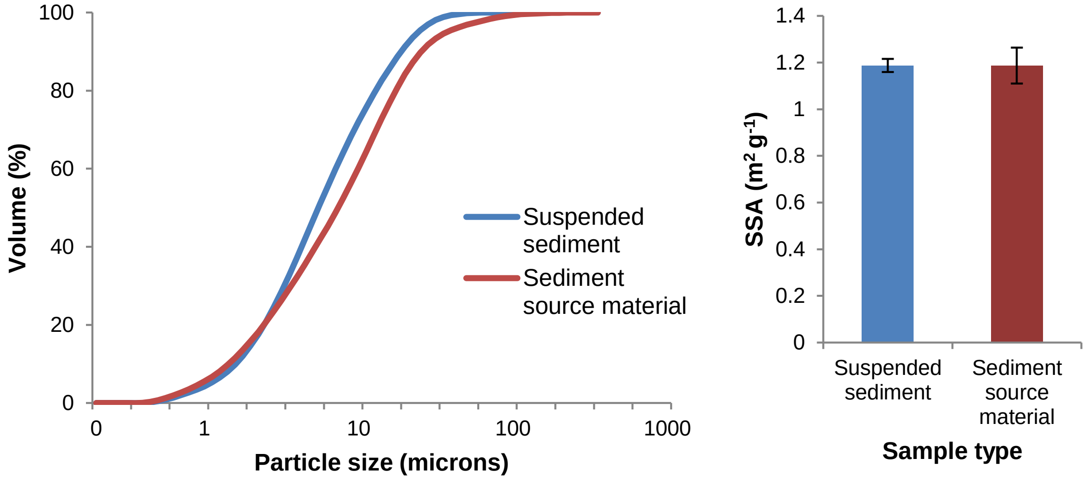

Figure 7.5 Comparison of the mean particle size composition and SSA values (with associated standard error) for the suspended sediment and source material samples for the Ridgemoor Brook sub-catchment.

The enrichment of fine material in suspended sediment is not as pronounced for the Curl Brook sub-catchment (Figure 7.6). Here the suspended sediment material is characterised by a silt-clay ratio of 9.61, a d_{50} of 13.78 µm and a SSA of 1.07 m^2 g^{-1}, whilst the equivalent values of the source material are 8.64, 17.67 µm and 1.05 m^2 g^{-1}, respectively. Although the suspended sediment is slightly finer than that of the source material, there is not a significant difference between the two, due to the overlap in associated standard errors. Although there is a statistical difference between the mean suspended sediment particle size and that of the source material in the Moor Brook sub-catchment (Figure 7.7), it is evident that the suspended sediment enrichment is limited to the < 14 µm and > 40 µm fractions. The source sediment is slightly more enriched in finer material between these fractions. The suspended sediment here is characterised by a silt-clay ratio of 7.36, a d_{50} of 10.28 µm and SSA of 1.29 m^2 g^{-1}, whilst the corresponding values for the mean source material are 8.42, 14.47 µm and 1.15 m^2 g^{-1} respectively.

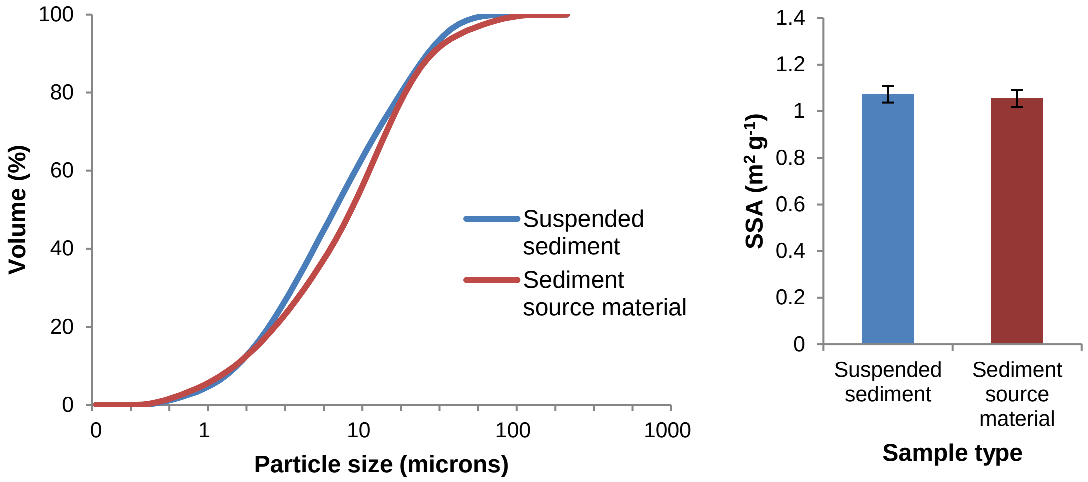

Figure 7.6 Comparison of the mean particle size composition and SSA values (with associated standard error) for the suspended sediment and source material samples for the Curl Brook sub-catchment.

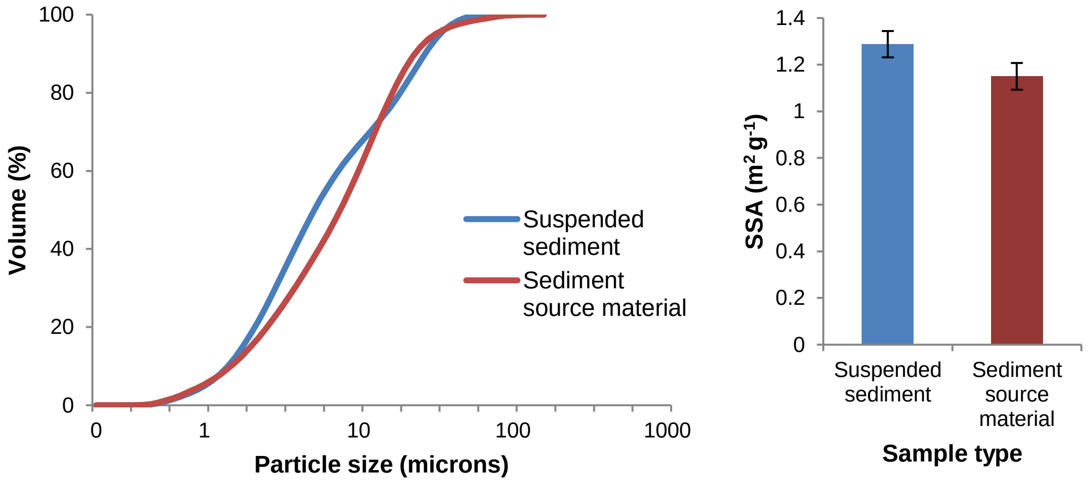

Figure 7.7 Comparison of the mean particle size composition and SSA values (with associated standard error) for the suspended sediment and source material samples for the Moor Brook sub-catchment.

7.4.2 Particle Size Correlation

The correlation between particle size (SSA estimates) and geochemical property concentration was analysed for individual samples within each sub-catchment using a Spearman’s rho test. This enabled the significance of the site-specific nature of property concentration dependence on particle size to be assessed, before a particle size correction factor could be applied to the raw data. The summary correlation results for each sub-catchment are shown in Table 7.28. The only sub-catchment to display a significant correlation between particle size and geochemical property concentration was Cheaton Brook. A total of 19 out of the available suite of 20 properties (95%) showed significant correlation at either the 0.05 or 0.01 levels of significance. In contrast, within the Ridgemoor Brook sub-catchment, only 4 properties (20%) showed a significant correlation with sample SSA, whereas only 2 properties (10%) and 3 properties (15%) displayed a significant correlation in the Curl Brook and Moor Brook sub-catchment respectively (Figure 7.8).

Table 7.28 Spearman's rho correlation coefficients and significance for particle size (SSA) and geochemical property concentrations for each sub-catchment.

	Cheaton Brook		**Ridgemoor Brook**		**Curl Brook**		**Moor Brook**	
Property	**Correlation Coefficient**	**Significance**	**Correlation Coefficient**	**Significance**	**Correlation Coefficient**	**Significance**	**Correlation Coefficient**	**Significance**
Na	0.722 (**)	0.004	-0.228	0.477	-0.328	0.252	0.140	0.648
Mg	0.766 (**)	0.001	0.004	0.991	-0.218	0.454	0.330	0.271
Al	0.859 (**)	0	0.655 (*)	0.021	0.509	0.063	0.347	0.246
K	0.775 (**)	0.001	0.112	0.729	-0.227	0.435	0.366	0.219
Ca	0.687 (**)	0.007	-0.294	0.353	-0.370	0.193	-0.055	0.858
V	0.890 (**)	0	0.813 (**)	0.001	0.670 (**)	0.009	0.569 (*)	0.042
Cr	0.823 (**)	0	0.750 (**)	0.005	0.419	0.136	0.710 (**)	0.007
Mn	0.841 (**)	0	-0.214	0.505	0.463	0.096	0.094	0.761
Fe	0.863 (**)	0	0.560	0.058	0.529	0.052	0.539	0.057
Co	0.859 (**)	0	0.567	0.054	0.500	0.069	0.454	0.119
Ni	0.854 (**)	0	0.669 (*)	0.017	0.628 (*)	0.016	0.589 (*)	0.034
Cu	0.757 (**)	0.002	0.560	0.058	0.178	0.542	0.278	0.358
Zn	0.762 (**)	0.002	0.091	0.778	-0.139	0.636	-0.039	0.901
As	0.638 (*)	0.014	0.438	0.155	0.132	0.652	0.209	0.493
Sr	0.669 (**)	0.009	-0.361	0.249	-0.308	0.283	-0.061	0.844
Mo	0.819 (**)	0	0.118	0.716	0.311	0.279	0.492	0.087
Ag	0.574 (*)	0.032	0.110	0.733	0.239	0.411	-0.123	0.688
Cd	0.567 (*)	0.035	0.037	0.909	0.438	0.117	0.008	0.979
Ba	0.664 (**)	0.010	-0.203	0.527	-0.189	0.517	0	1
Pb	0.033	0.910	0.378	0.225	0.520	0.057	-0.091	0.768

* Correlation significant at p = 0.05
** Correlation significant at p = 0.01

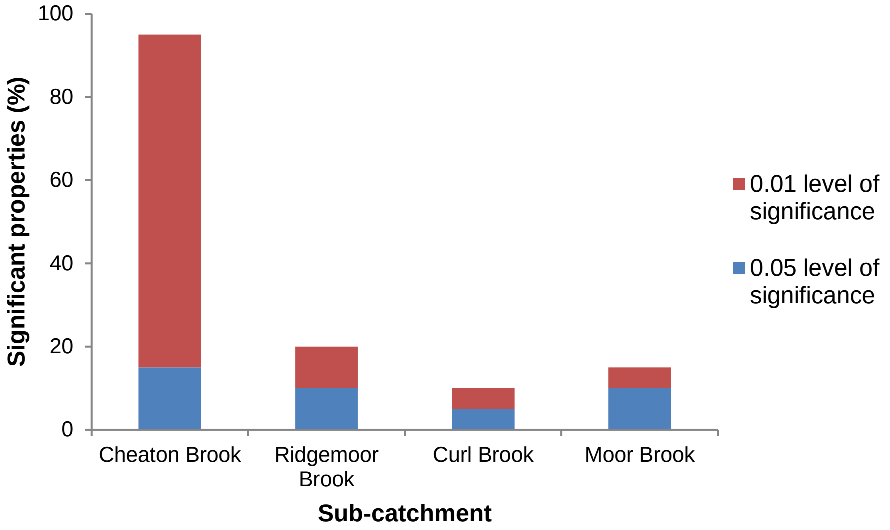

Figure 7.8 Percentage of properties showing a significant correlation between particle size (SSA) and geochemical property concentrations at the 0.05 and 0.01 levels of significance for each sub-catchment following the Spearman's rho test.

The limited number of geochemical properties displaying significant correlation between concentration values and particle size (SSA) within the Ridgemoor Brook, Curl Brook and Moor Brook sub-catchments renders the application of particle size correction factors inappropriate in these areas. On this basis, any over-simplification of the relationship between SSA and property concentration and subsequent over-correction of particular properties is avoided.

Therefore, with the exception of Cheaton Brook, it was therefore assumed that by confining the sediment fingerprinting analysis to the < 1 mm fraction during the processing phase, property concentration particle size dependencies and grain size composition contrasts had been adequately accounted for. Consequently, it was considered that additional corrections within these sub-catchments were not necessary to compare property concentration values.

When calculating the correction factors for the Cheaton Brook sub-catchment suspended sediment samples were treated individually Their SSA values were highly variable over different flow conditions (Figure 7.9), which could have an effect on the calculated particle size correction factor. For example, it is evident that very fine material was transported during 'Sep-Oct 12', producing a SSA of

1.49 m^2 g^{-1}, whilst a SSA value of 1.05 m^2 g^{-1} indicated that coarser sediment was transported during ‘6th-13th Jul 12’. It is therefore likely that the correction factors will be different for each suspended sediment sample.

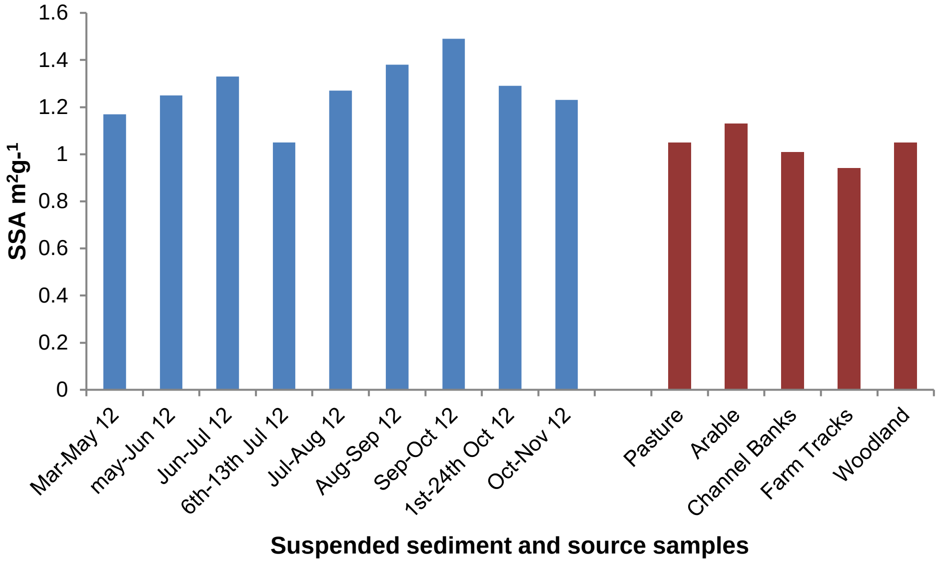

Figure 7.9 Particle size (SSA) values for the individual suspended sediment samples and mean source groups for the Cheaton Brook sub-catchment.

In addition, Figure 7.9 illustrates the differences between the SSA of the individual suspended sediment samples and the corresponding SSA values for the source material in the Cheaton Brook sub-catchment. It is apparent that the arable source group comprised the finest sediment with a SSA of 1.13 m^2 g^{-1}, whereas the farm track source group contained particularly coarse material producing a SSA value of 0.94 m^2 g^{-1}. Although the arable source group was finer than the coarsest suspended sediment sample, the suspended sediment samples are generally enriched in fines compared to the corresponding source samples, which could reflect the particle size selectivity during sediment transportation (Collins, 2008). This further demonstrates the necessity of a particle size correction factor for this particular sub-catchment.

7.5 Application of Mixing Model

The composite fingerprint identified in the sediment source discrimination phase for each sub-catchment was integrated into a numerical mixing model (see Chapter 5) to estimate the relative contribution of fine sediment being delivered from different source types to individual suspended sediment samples. As previously identified in Table 7.28, Cheaton Brook was the solitary sub-catchment that exhibited significant correlations between geochemical concentrations and particle size (SSA). As a result, particle size correction factors were only incorporated into the mixing model algorithm for this particular sub-catchment. The particle size correction factors were calculated by utilising the ratio of the SSA of each individual suspended sediment sample to the corresponding mean SSA value of the source material from each source group (Table 7.29).

Table 7.29 Particle size correction factors incorporated into the mixing model for the Cheaton Brook sub-catchment.

Sink sample	Arable	Pasture	Channel banks	Woodland	Farm tracks
Mar-May 12	1.04	1.11	1.16	1.11	1.24
May-Jun 12	1.11	1.19	1.24	1.19	1.33
Jun-Jul 12	1.18	1.27	1.32	1.27	1.41
6th-13th Jul 12	0.93	1.00	1.04	1.00	1.11
Jul-Aug 12	1.12	1.21	1.26	1.21	1.35
Aug-Sep 12	1.22	1.31	1.37	1.31	1.46
Sep-Oct 12	1.32	1.42	1.48	1.42	1.58
1st-24th Oct 12	1.14	1.23	1.28	1.23	1.37
Oct-Nov 12	1.09	1.17	1.22	1.17	1.31
Mean	**1.13**	**1.21**	**1.26**	**1.21**	**1.35**

It is evident from Table 7.29 that the particle size correction factors vary over time, which demonstrates the importance of treating each suspended sediment sample independently. Large correction factors are associated with samples comprised of coarse sediment (e.g. 'Sep-Oct 12'), whereas finer sediment samples create smaller particle size correction factors (e.g. '6th-13th Jul 12'). As a result, there are large differences between the particle size correction factors generated by using the individual suspended sediment SSA, and that of the mean suspended sediment SSA (Table 7.29). The mean suspended sediment SSA has been utilised in the calculation of the particle size correction by Collins *et al*. (1997a; 2009; 2010b), yet in this study such an approach would obscure the large spatiotemporal variation in particle size. Hence correction factors by sample were subsequently incorporated into the mixing model algorithm for the Cheaton Brook sub-catchment.

The mixing model algorithm for each sub-catchment also incorporated property-specific discrimination weightings to account for the variable contributions made by different properties to the overall composite fingerprint discrimination. Individual weightings were based on the relative discriminatory efficiency of each property within the composite fingerprint and were derived from the entry of individual properties into the DFA process (see Chapter 5). Table 7.30 presents the property-specific discriminatory weightings for each sub-catchment.

Table 7.30 Property-specific discrimination weightings for each sub-catchment.

Fingerprint property	Individual discrimination (%)	Tracer weighting	Fingerprint property	Individual discrimination (%)	Tracer weighting
Cheaton Brook			**Ridgemoor Brook**		
Mg	32.9	1.12	Mo	52.5	1.60
Cr	39.0	1.33	Fe	39.3	1.20
Mo	50.0	1.71	Cr	32.8	1.00
Ba	29.3	1.00	V	41.0	1.25
V	37.8	1.29	Al	36.1	1.10
Al	36.6	1.25	K	42.6	1.30
Fe	31.7	1.08	Pb	44.3	1.35
Pb	37.8	1.29	Zn	41.0	1.25
Ag	37.8	1.29			
Curl Brook			**Moor Brook**		
Al	32.9	1.79	Al	50.0	2.00
V	28.9	1.57	Cu	42.9	1.72
Zn	40.8	2.22	Ba	28.6	1.14
Ni	35.5	1.93	Cd	25.0	1.00
Mg	18.4	1.00	Ni	53.6	2.14
Mo	44.7	2.43	Mg	53.6	2.14
Cr	28.9	1.57	V	42.9	1.72
Cd	40.8	2.22			

It is evident that Mo produces the greatest individual discrimination and therefore, exerts the strongest influence on the mixing model iterations in three out of the four sub-catchments (Cheaton Brook, Ridgemoor Brook and Curl Brook). This could reflect the specific land-use within the particular sub-catchments. For instance, legumes, which were frequently identified during field reconnaissance in the Cheaton Brook, Ridgemoor Brook and Curl Brook sub-catchments, require more Mo than grasses (McBride *et al.,* 2000). It has been acknowledged that Mo has a relatively high potential for leaching, particularly in fine sandy soils (Kaiser *et al.,* 2005), which is common in the Lugg catchment.

As a result, fertilisers are required to add Mo to the soil in fields consisting of legumes. Elevated source type discrimination within these specific sub-catchments can therefore be generated, as soil from particular land use types will have varying levels of Mo. However, it was apparent during field reconnaissance that grasses dominate the Moor Brook sub-catchment, which could subsequently reflect the exclusion of Mo in the final composite fingerprint generated for this sub-catchment.

It is also evident that Al and V are included in the final composite fingerprint in each of the four sub-catchments, which indicates the importance of these particular properties in affording optimum discrimination between source types. For instance, the presence of Al in the individual source samples could be caused by the formation of Al-phosphate complexes or precipitants following the consistent field application of phosphate-based fertilisers (Haynes and Naidu, 1998; Chiang *et al.,* 2008). Fertilisers are commonly applied to agricultural soils in the Lugg catchment to maintain or improve crop yields and as a result, large amounts of Al are generally found within these soils. In contrast, V can naturally occur as a trace element in soils and sediments (Cappuyns and Slabbinck, 2012). The concentration of V in the source samples can originate from the decomposition and weathering of the underlying parent material. As a result, small amounts of V occur in sandstone (Fischer and Ohl, 1970), which is the dominant geology of the Lugg catchment. This trace element can therefore be discovered in varying amounts within the topsoil, hence its significance in the discrimination process.

These tracer-specific weightings and site-specific particle size corrections were incorporated within the mixing model algorithms to more reliably estimate the relative contribution of fine sediment being delivered from different source types to individual suspended sediment samples in each sub-catchment. The results of this sediment sourcing procedure are shown in the following chapter.

CHAPTER 8
FINE SEDIMENT SOURCES AT THE SUB-CATCHMENT SCALE

8.1 Introduction

This chapter presents the results and interpretation from the sediment source fingerprinting procedure applied to suspended sediment samples collected from four of the sub-catchments identified as persistent contributors of fine sediment (see Chapter 6). From an assessment of the amount and frequency of sediment individual sub-catchments contribute to the monitoring sites, four sub-catchments were selected (see Chapter 3, section 3.3). The aim of this procedure was to identify sub-catchment sources of fine sediment based on differing land use types. The field methodology and sediment source fingerprinting technique detailed in Chapters 3 and 5 have been applied to establish any spatial and temporal variations in the contributions of different source types in each sub-catchment.

The output from the mixing models for the four sub-catchments provided estimates of the relative source group contributions over different flood events during the study period (March – November 2012). It is important to recognise that these results are specifically presented as relative contributions and do not represent the absolute importance of a particular source. For example, a high relative contribution may not necessarily reflect a high quantity of sediment, in circumstances where the total sediment load is substantially low (Walling *et al*., 2008; Collins *et al*., 2010b). The sediment source ascription results are divided into two sections in order to identify and interpret the spatial and temporal variations in source apportionment for the individual sub-catchments. The spatial variation section reports the mean relative source contributions for each sub-catchment over the entire period of study, which are weighted according to the instantaneous suspended sediment load at the time of sampling (see Chapter 5, equation 5.4). This variation is considered in context of the prevailing land use in each sub-catchment. However, the mean values conceal considerable inter-storm variability in the contribution of the individual source groups (Walling *et al.,* 1999b). As a result, the temporal variation section examines the differences in suspended sediment sources during different storm events for each sub-catchment. This inter-storm variation is discussed in context of land use activities, along with rainfall characteristics throughout the individual sampling periods.

8.2 Spatial Variation

The load-weighted mean sediment source apportionment and associated Relative Mean Error (RME) for each sub-catchment over the entire study period are presented in Table 8.1. The RME (see chapter 5) for the combined sediment apportionment estimates ranged from 6.9% in the Ridgemoor Brook sub-catchment, to 14.1% in the Moor Brook sub-catchment. This indicated a mean goodness-of-fit ranging from 93.7% to 85.9%. It has been suggested that a RME of < 15% indicates that the mixing models have provided an acceptable prediction of the suspended sediment fingerprint property concentrations (Collins *et al.,* 1997c; Collins and Walling, 2000). Further, the RME values in this study compare favourably with those attained in other fingerprinting studies (for example, Minella *et al.,* 2008; Collins *et al*., 2009; 2010a; Haley, 2010). Based on the RME values obtained, it was assumed that the mixing models were capable of successfully predicting sediment provenance in each of the four sub-catchments.

Table 8.1 Load-weighted mean sediment source apportionment and associated RME for each sub-catchment.

Sub-catchment	**Estimated sediment contribution (%)**					**RME (%)**
	Pasture	**Arable**	**Channel banks**	**Woodland**	**Farm tracks**	
Cheaton Brook	8	5	19	21	47	8.7
Ridgemoor Brook	29	32	22	-	17	6.9
Curl Brook	19	3	21	2	55	9.4
Moor Brook	15	2	18	-	65	14.1

The load-weighted mean relative contributions from individual source groups to the suspended sediment samples collected from the outlets of each sub-catchment are presented in Figure 8.1. It is evident that significant contrasts exist between the relative sediment source contributions for the four sub-catchments. In the case of the Cheaton Brook sub-catchment farm track surfaces represented the dominant source of fine sediment, contributing 47% of the total suspended sediment. Inputs from woodland topsoils were estimated to be 21%, while channel bank sources contributed 19% of the total suspended sediment. Eroding pasture and arable surface soils represented the least significant sources of fine sediment within this sub-catchment, with respective contributions estimated to be 8% and 5%. In contrast, fine sediment sources from pasture and arable topsoils were predicted to be more important in the Ridgemoor Brook sub-catchment, contributing 29% and 32% of the total suspended sediment respectively. These represented the dominant sources of fine sediment in this sub-catchment, with an additional 22% of the total suspended sediment contributed by channel banks. Relative sediment inputs from eroding farm track surfaces provided 17% to the total suspended sediment, the smallest source of suspended sediment in this sub-catchment (Figure 8.1). In comparison, farm track surfaces represented the most significant source of fine sediment in the Curl Brook sub-catchment, providing 55% of the total suspended sediment. Eroding channel banks and pasture surface soils were also estimated as important sources of suspended sediment, supplying 21% and 19% respectively. Eroding arable surface soils and woodland topsoils represented the least important sources of fine sediment in this sub-catchment, with respective contributions estimated to be only 3% and 2% (Figure 8.1). Similarly, farm track surfaces were estimated to represent the dominant source of fine sediment in the Moor Brook sub-catchment, contributing 65% of the total suspended sediment. In contrast, eroding arable surface soils represented the least significant source of fine sediment within this sub-catchment, with a limited supply estimated to be 2%. Channel banks and pasture topsoils were additionally estimated to be important sources of fine sediment, adding 18% and 15% of the total suspended sediment respectively (Figure 8.1).

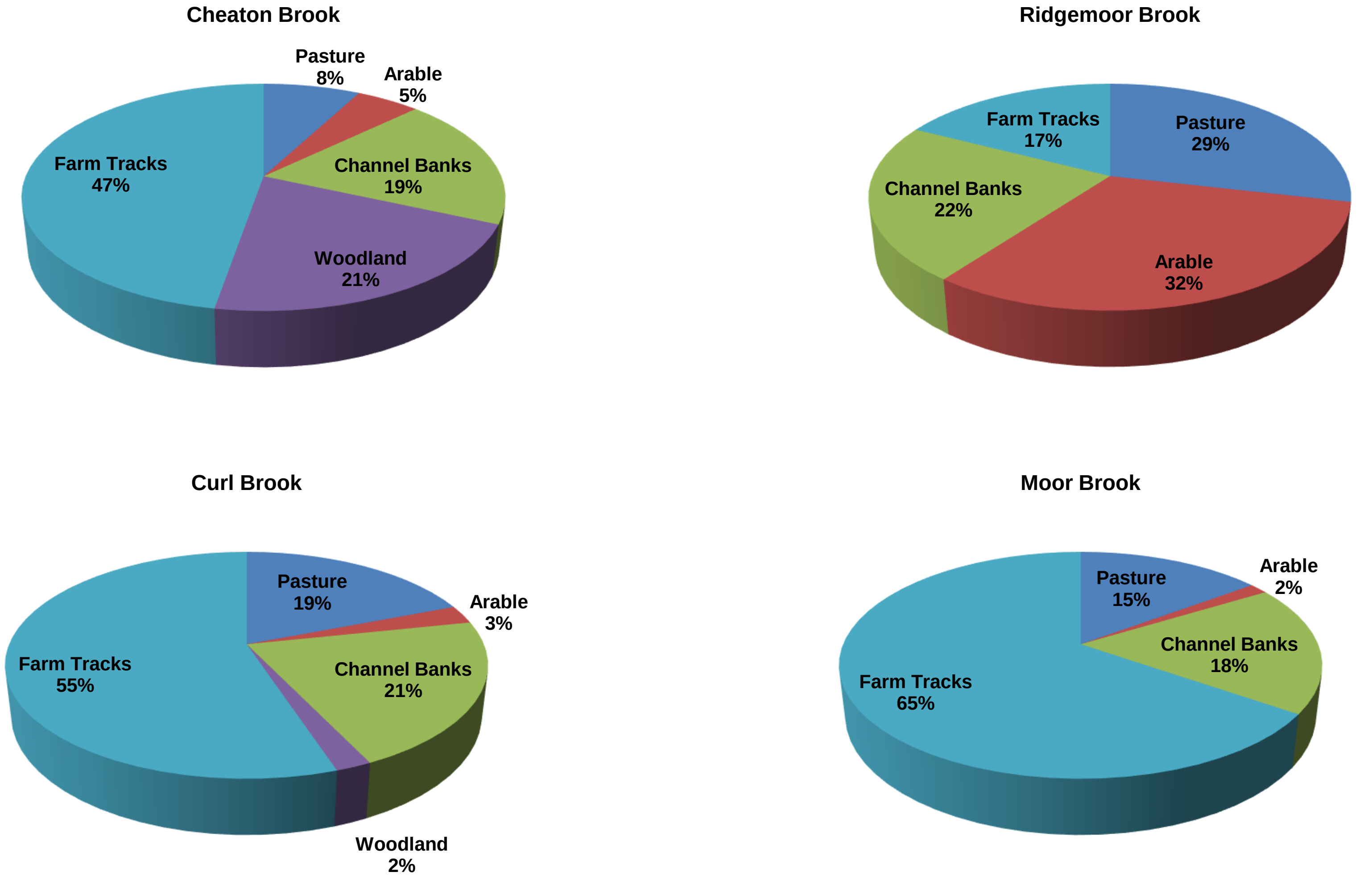

Figure 8.1 The load weighted mean relative proportions of sediment from the four sub-catchments (March – November 2012).

8.2.1 Farm Tracks

Figure 8.2 further illustrates the contrasting load-weighted mean relative sediment source contributions based on individual source types within the four designated sub-catchments. It is particularly evident that the predominant source of suspended sediment collected from the catchment outlets of three out of the four sub-catchments was farm track surfaces. This fine sediment source type contributed 65%, 55% and 47% of the total suspended sediment in the Moor Brook, Curl Brook and Cheaton Brook sub-catchments respectively. Given that the proportion of total land area occupied by such linear features is small, the disproportionately high contribution to total suspended sediment is surprising. Nevertheless, unlike other sediment source types, unmetalled farm tracks not only contribute to the suspended sediment load as one of the primary sources but can also potentially provide pathways for the efficient delivery of material mobilised from alternative sources (MacDonald and Coe, 2008; Collins *et al*., 2010c; Fu *et al*., 2010). Collins *et al.* (2012a) reported that fine grained sediment contributions from farm track surfaces ranged from 45% to 73% in the agricultural River Kennett catchment, Southern England, with a mean contribution estimated at 55%. Collins *et al.,* (2010c) also suggested that through visual observations during storm events farm tracks delivered ca. 90% of sediment mobilised from agricultural land in the River Piddle catchment, Southern England. Owing to the agricultural nature of the River Lugg (see Chapter 2), farm tracks are generally prevalent in the catchment, providing direct links between fields and farm land. The surfaces are typically ungraded and are thus frequently damaged, degraded and subsequently compacted due to the extensive use of heavy farm machinery and livestock trampling, which exaggerates runoff potential and erosion risk (Ziegler *et al*., 2000; Motha *et al*., 2004; Sheridan and Noske, 2007; Collins *et al*., 2010c; 2012a). As the farm tracks are generally well connected to the channel network within these sub-catchments, mobilised sediment is efficiently delivered to the channel system (Collins *et al.,* 2010c). Therefore, the large provenance signature of suspended sediment from eroding farm track surfaces within agricultural catchments is not entirely unexpected.

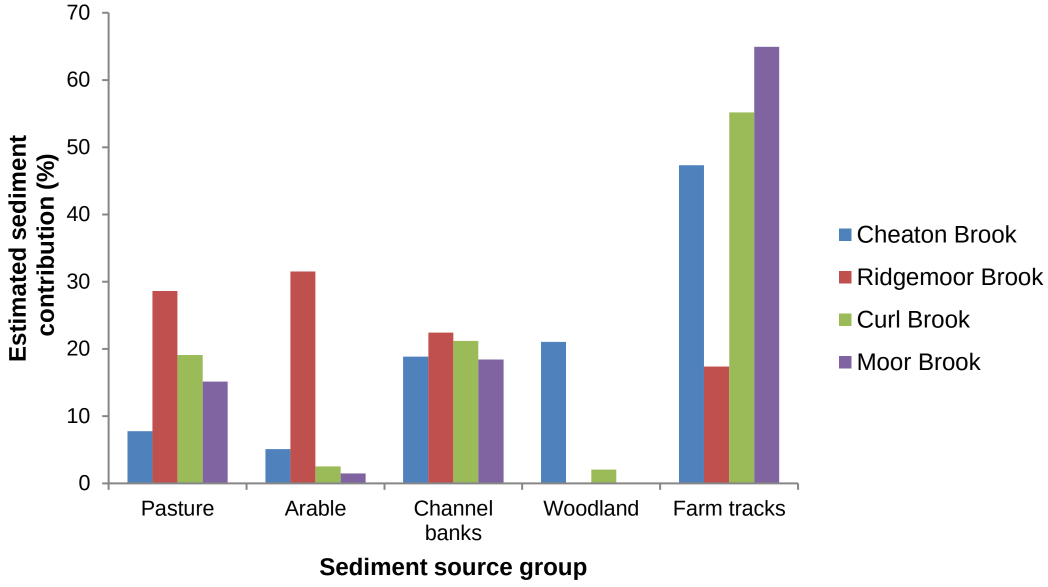

Figure 8.2 Estimated source type contributions for each sub-catchment, based on the load weighted mean relative proportions.

However, farm track surfaces represented the least significant source of fine sediment in the Ridgemoor Brook sub-catchment, contributing only 17% of the total suspended sediment (Figure 8.2). This could reflect the relative differences in the location of farm tracks within the four sub-catchments and the associated connectivity with the channel network, along with how frequently the tracks are used. In the Cheaton, Curl and Moor Brook sub-catchments, farm tracks are commonly located in close proximity to the channel network, with many in-channel crossings (Figure 8.3). Consequently, they are directly connected to the river channel system, with steep slopes encouraging significant erosion during heavy rainfall events and the delivery of loose erodible material, especially evident in the Cheaton and Curl Brook. In contrast, farm tracks in the Ridgemoor Brook sub-catchment demonstrated lower connectivity as they are generally located adjacent to the channel network, characterised by smaller slopes with only sporadic in-channel crossings evident (Figure 8.4). As a result, the delivery of fine sediment mobilised from the farm tracks in this sub-catchment is significantly reduced. When considering the topography of all four sub-catchments, it is evident that the Cheaton and Curl Brook sub-catchments are characterised by high elevation compared to the Ridgemoor and Moor Brook (Figure 8.5). This suggests that differences in topography (slope and elevation) may have an influence on the importance of farm track sources, as this source type represents the most significant source of sediment in these two sub-catchments. However, although the Moor Brook sub-catchment is also associated with the greatest sediment contributions from farm track surfaces, it is characterised by low relief and an average slope of 2.6% (see Table 6.3). Therefore, differences in topography may not fully reflect the variations in sediment contributions from this source type.

Figure 8.3 Typical characteristics of farm tracks located in the Cheaton Brook, Curl Brook and Moor Brook sub-catchments, demonstrating greater connectivity with the channel network and extensive surface damage.

It was also evident throughout the field reconnaissance, that there was a significant difference in the extent of wheel rutting and surface damage through poaching associated with the farm tracks located in the different sub-catchments. The extent of surface damage and degradation in the Cheaton, Curl and Moor Brook sub-catchments (Figure 8.3) was identified to be much greater than farm tracks in the Ridgemoor Brook sub-catchment (Figure 8.4). This could indicate that farm tracks within Ridgemoor are less frequently used compared to the tracks located in the other three sub-catchments, where frequent vehicular traffic and livestock movement can disturb the track surfaces and promote efficient delivery of fine sediment (Motha *et al.,* 2004). Mobilised sediment generated from the infrequently used farm tracks in the Ridgemoor Brook sub-catchment is therefore significantly lower.

Figure 8.4 Typical characteristics of the less frequently used farm tracks in the Ridgemoor Brook sub-catchment, demonstrating lower connectivity with the channel network and a deficiency in surface degradation.

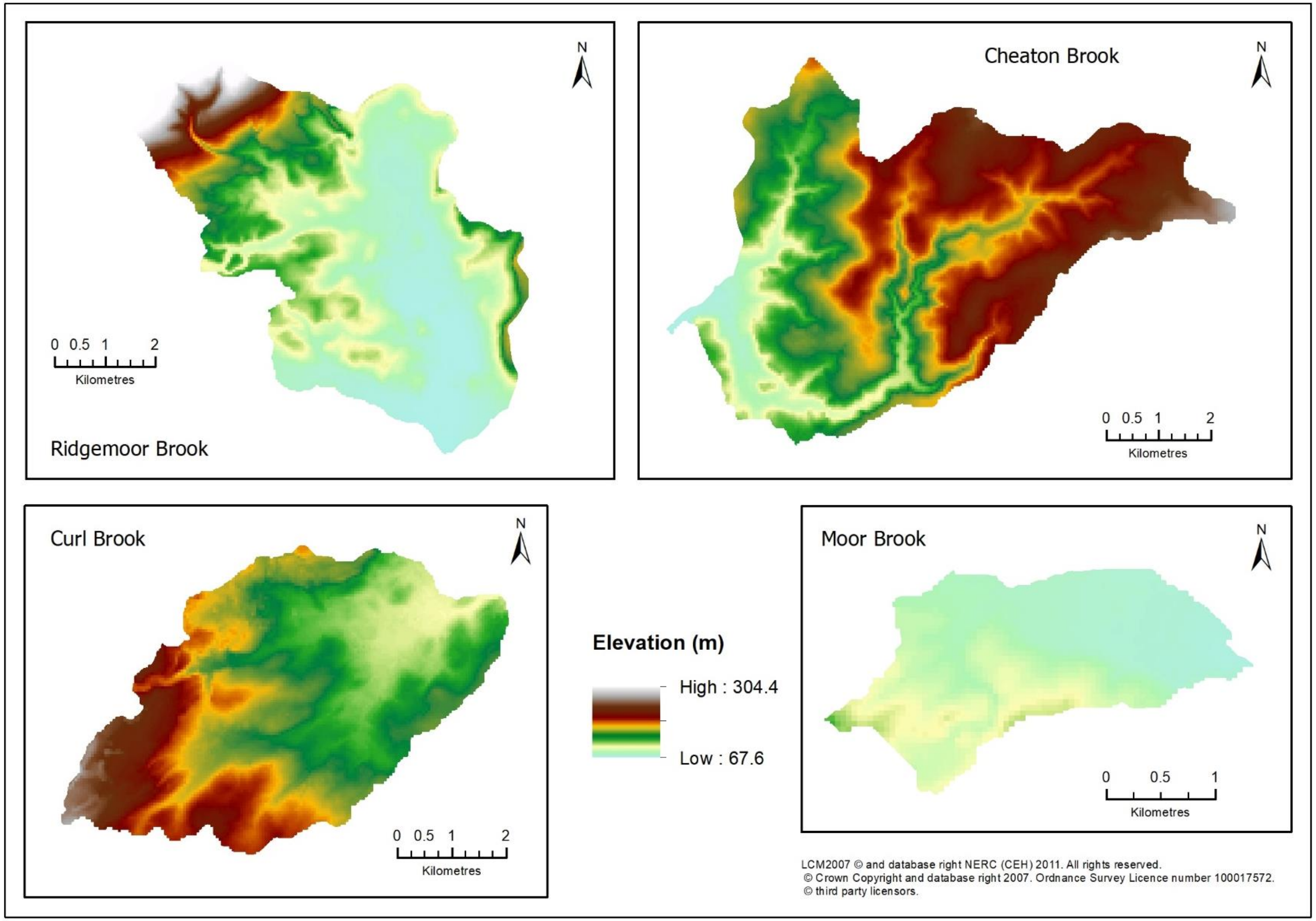

Figure 8.5 Digital Elevation Models of the four sub-catchments (OS data © Crown copyright and database rights 2018).

8.2.2 Arable

It is clear from Figure 8.2 that there is a large variation in the contribution of arable sources to the suspended sediment collected at the outlets of the four sub-catchments. Although sediment mobilisation was observed from arable surfaces during the collection of representative source material samples, the contributions in three out of the four sub-catchments appear to be relatively insignificant. This fine sediment source type contributed 5%, 3% and 2% of the total suspended sediment in the Cheaton, Curl and Moor Brook sub-catchments respectively. However, it is evident that this fine sediment source type is the predominant supplier of suspended sediment in the Ridgemoor Brook sub-catchment with a contribution of 32%. When considering the prominent spatial extent of arable farming within the four sub-catchments (see Figure 3.15), it is perhaps surprising that the apportionment results only demonstrate the significance of this particular source type in the Ridgemoor Brook sub-catchment. The dominance of arable land cover, recent intensification of potato cultivation in the Lugg catchment and the importance of autumn-sown cereals would all suggest a high erosion risk (Walling *et al.,* 1999a; Evans, 2002; Walling, 2005; Collins and Walling, 2007; Collins *et al*., 2010b). The relative source contributions do not appear to reflect the proportion of arable land area (Haley, 2010). This relationship is illustrated in Figure 8.6; the greatest arable sediment contribution is observed in the sub-catchment with the lowest spatial coverage (Ridgemoor Brook), whilst the least significant sediment contribution is detected in the sub-catchment with the greatest areal extent (Moor Brook). This indicates that factors in addition to spatial coverage control sediment mobilisation and delivery from arable sources (Collins *et al*., 2010b). These factors could include the location of arable fields in a particular sub-catchment and the connectivity between arable fields and the river channel network, including the extent and type of channel margins, as well as the catchment characteristics.

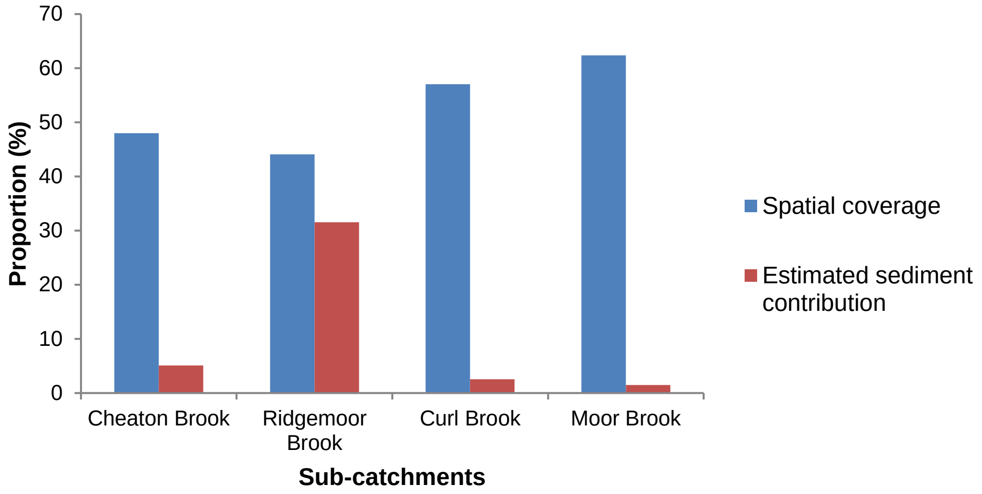

Figure 8.6 The proportion of land area occupied by arable surfaces and the associated relative sediment contributions from each sub-catchment.

Sediment mobilisation and delivery from arable surface sources could be controlled by the connectivity and location of arable fields within a particular sub-catchment, which would conceal the sediment associated effects of increases in spatial coverage. It was apparent throughout field reconnaissance in the Cheaton Brook sub-catchment that most of the intensive arable farming, in particular potato cultivation, was confined to fields located in the upper parts of the catchment. This is further highlighted when considering the land cover of all field parcels located adjacent to the watercourse in each sub-catchment (Figure 8.7). The majority of arable fields directly connected to the watercourse in the Cheaton Brook are located in the upper parts of the catchment, whereas equivalent fields appeared in both the upper and lower reaches of the Ridgemoor and Curl Brook sub-catchments. As a result, sediment mobilised from the arable source category within the latter two sub-catchments is only entrained in the river channel network for a relatively short amount of time before it is routed out through the catchment outlet, where it was subsequently sampled. Conversely, the sediment mobilised from this source type in the Cheaton Brook sub-catchment is entrained within the channel for much longer periods and is therefore subjected to conveyance losses such as those associated with overbank deposition (Walling *et al.,* 1999b). Consequently, the likelihood of fine sediment becoming deposited and stored within the channel when velocities are reduced between flood events is significantly increased in these sub-catchments.

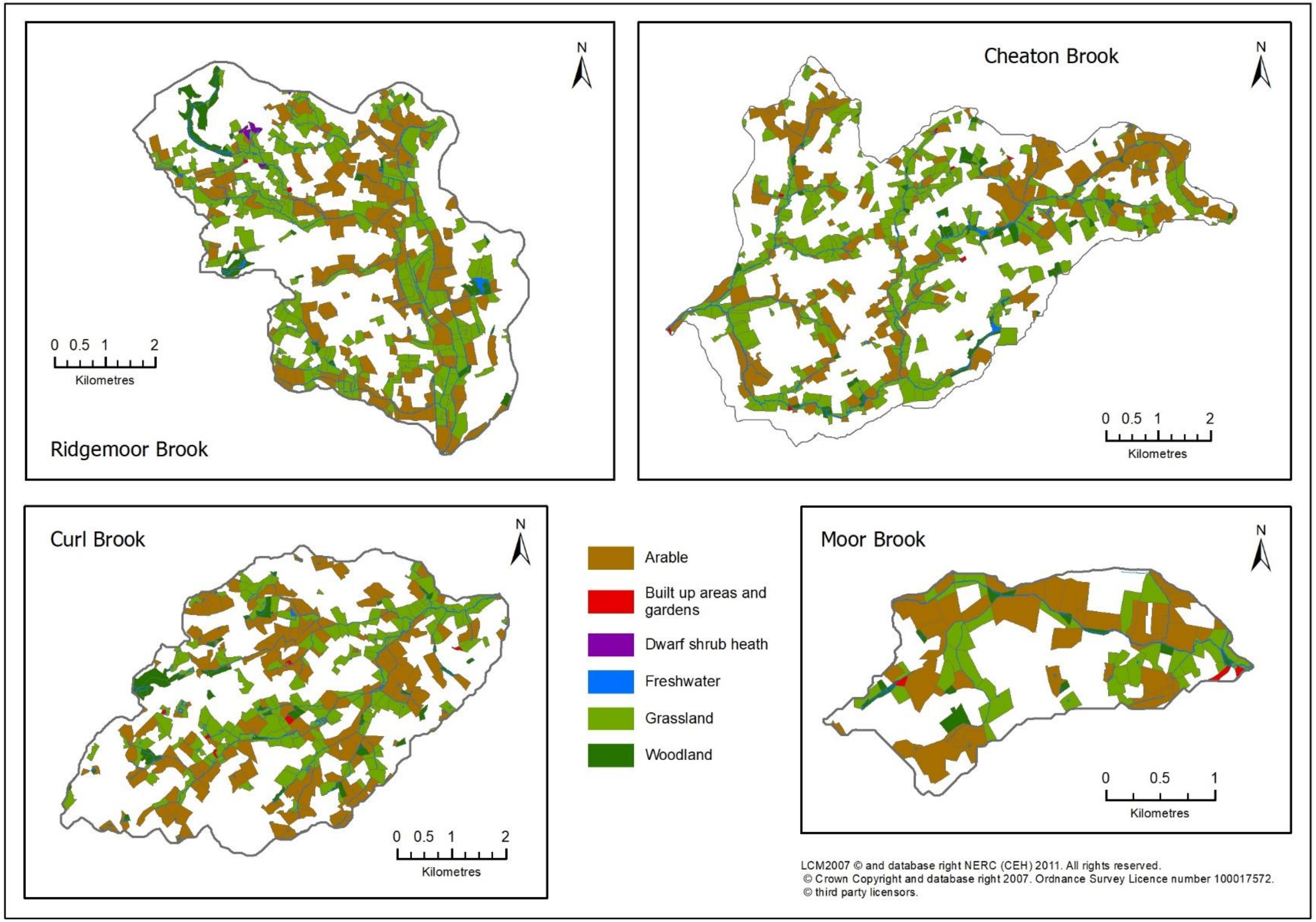

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Figure 8.7 Land cover connectivity maps showing field parcels located adjacent to the watercourse in each sub-catchment.

Factors affecting connectivity between arable surfaces and the channel network within a particular sub-catchment could also control variations in sediment mobilisation and delivery from this source category. Field reconnaissance demonstrated the prevalence of large channel margins and edge-of-field buffer strips associated with the majority of arable fields within the Cheaton, Curl and Moor Brook sub-catchments (Figure 8.8). This effectively minimises sediment delivery to the channel network by trapping the mobilised sediment, which may assist in accounting for the low contributions from the arable source category to the total suspended sediment collected in these sub-catchments. The importance of edge-of-field buffer strips in reducing the sediment contribution from arable topsoils was demonstrated in the River Kennet catchment where mobilised sediment was trapped before reaching efficient delivery pathways; as a result, arable topsoil sediment contributions were estimated at only 4% (Collins *et al.,* 2012a). In contrast, it was evident that arable fields located in the Ridgemoor Brook sub-catchment were characterised by much smaller channel margins, with evidence of runoff indicating that these were ineffective in minimising sediment delivery to the river channel system (Figure 8.9). This therefore, reflects the large contribution from the arable source category to the suspended sediment collected in this sub-catchment, and consequently the variation in contributions from each sub-catchment illustrated in Figure 8.2.

Figure 8.8 Typical characteristics of arable fields located in the Cheaton Brook, Curl Brook and Moor Brook sub-catchments, associated with large channel margins and edge-of-field buffer strips.

Figure 8.9 Typical characteristics of arable fields located in the Ridgemoor Brook sub-catchment, associated with much smaller channel margins.

Variations in the characteristics of individual sub-catchments can also have an effect on sediment mobilisation and delivery from this source category. It was evident from field reconnaissance that arable fields directly connected to the watercourse in the Moor Brook sub-catchment are characterised by low relief with only moderate slopes. This is highlighted in Figure 8.10, which shows the relief associated with the field parcels directly connected to the watercourse (Figure 8.10). Poor connectivity was visible between arable surfaces and the channel network, with no evidence of major runoff or efficient delivery pathways during heavy rainfall events (Figure 8.11). This reflects the low sediment contributions from the arable source category associated with this sub-catchment. Conversely, the Ridgemoor Brook sub-catchment is characterised by steeper slopes (see Table 6.3) and therefore, the potential for topsoil erosion is much greater. Although, many of the arable fields directly connected to the watercourse in this sub-catchment are located in areas characterised by low relief (Figure 8.10), field reconnaissance highlighted visible runoff and active delivery pathways. This is suggestive of an enhanced connectivity between arable surfaces and the river channel network (Figure 8.12). It was therefore not surprising that the apportionment results confirmed a greater sediment contribution from the arable source category in the Ridgemoor Brook sub-catchment.

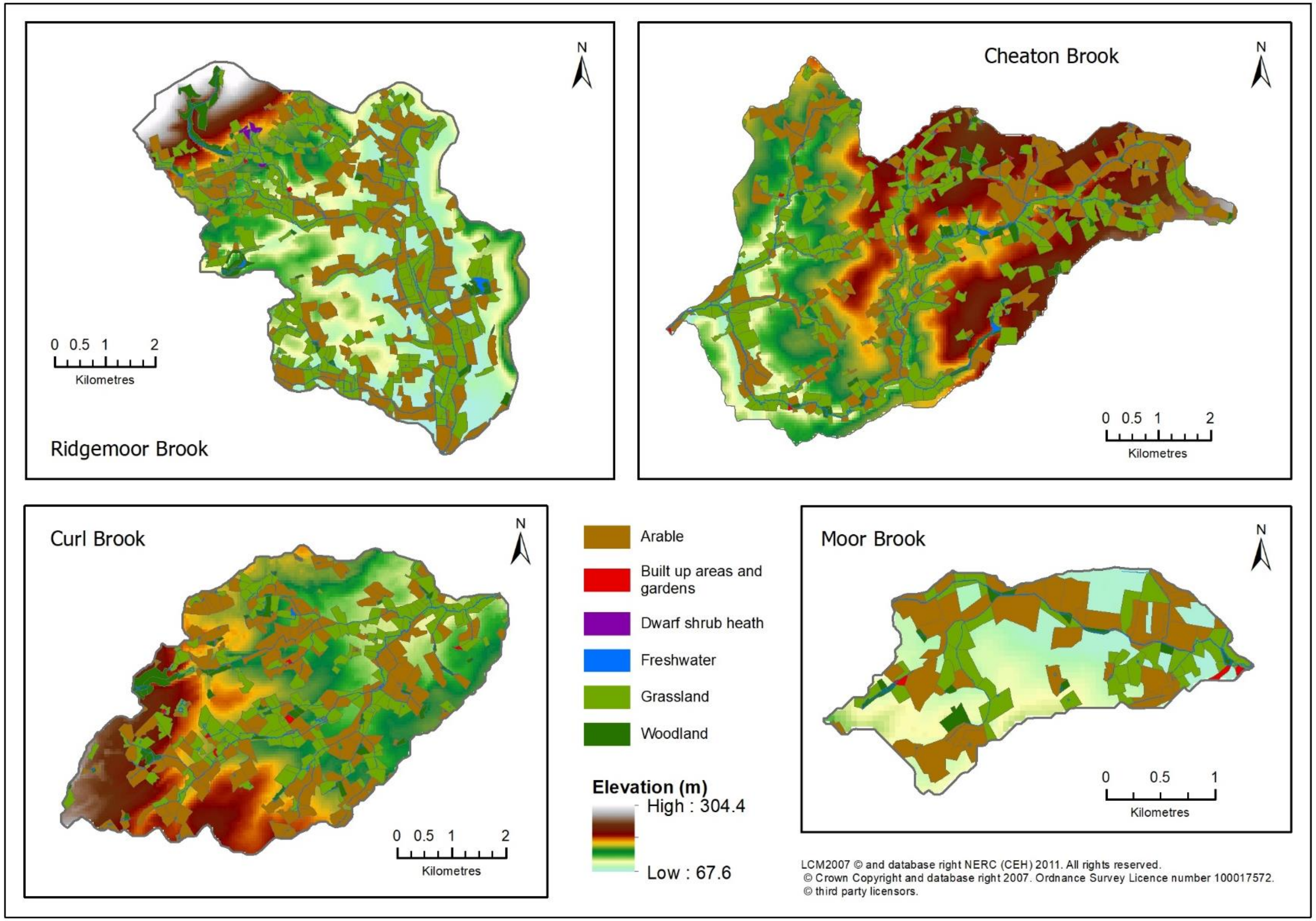

Figure 8.10 Digital Elevation Models and land cover connectivity maps for each sub-catchment.

Figure 8.11 Examples of arable fields located in the Moor Brook sub-catchment which are typically associated with low relief with gently-inclined slopes.

Figure 8.12 Examples of arable fields typically located on steeper slopes in the Ridgemoor Brook sub-catchments and associated with active runoff pathways.

However, differences in catchment characteristics may not independently reflect the variations in sediment contributions illustrated in Figure 8.2. For example, whilst arable surface contributions were low for the Cheaton Brook sub-catchment, most of the more intensive arable fields directly connected in the watercourse are located in areas of higher relief and on steep slopes with risks of erosion and sediment mobilisation (Figure 8.10). The connectivity between these slopes and the river channel system is also enhanced by the local road network (Walling *et al*., 2002), which amplifies the efficient runoff and subsequent delivery of the mobilised sediment to the downstream channel (Figure 8.13). Nevertheless, the majority of these fields are located in the upper parts of the sub-catchment (Figure 8.7) and as a result, sediment delivered from this source can become deposited within the channel. This, along with effective breaks in slope associated with the limited number of steeply inclined fields in the mid-to-lower parts of the sub-catchment, prevented the mobilisation of sediment from the arable source category having an impact on the sediment system in the Cheaton Brook sub-catchment.

Figure 8.13 Example of an arable field located on a steeply inclined slope in the upper part of the Cheaton Brook sub-catchment, demonstrating enhanced runoff and sediment delivery through the local road network.

8.2.3 Pasture

Like the farm track and arable source categories, there is evidence of contrasting sediment contributions from pasture surface sources in the four sub-catchments (Figure 8.2). For instance, surface erosion from areas of pasture represented a significant source of fine sediment in the Ridgemoor Brook sub-catchment, contributing 29% of the total suspended sediment. It is also apparent that pasture topsoils represented an important source of suspended sediment in the Curl and Moor Brook sub-catchments, with respective contributions of 19% and 15%. However, although sediment mobilisation was also frequently observed through poaching of grazed pasture surface soils during the collection of representative source material samples in the Cheaton Brook sub-catchment, the contributions appear to be relatively insignificant. Only 8% of the total suspended sediment was attributed to pasture sources within this sub-catchment. When considering the spatial extent of pasture within the four sub-catchments the apportionment results demonstrate that, like the arable source category, the significance of relative source contributions does not reflect the associated spatial coverage. This can be distinguished in Figure 8.14, where the smallest pasture sediment contribution is detected in the sub-catchment with the greatest spatial coverage. For example, pasture accounts for 47% of the total land use and 52% of the land use adjoining the channel network in the Cheaton Brook sub-catchment, yet despite this, the load-weighted mean pasture contribution is relatively low.

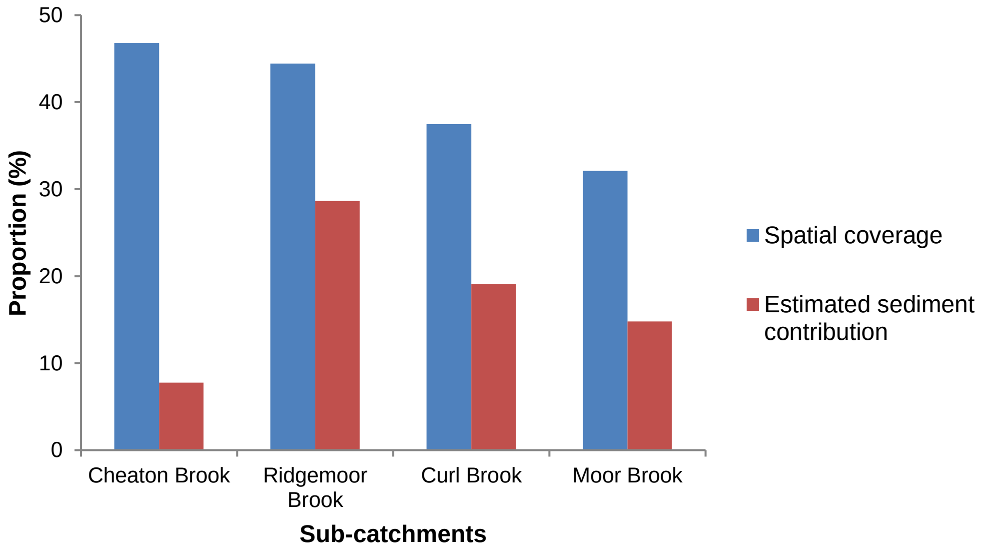

Figure 8.14 The proportion of land area occupied by pasture surfaces and the associated relative sediment contributions from each sub-catchment.

Placed in context with the arable source category, the application of the source fingerprinting technique has illustrated that sediment contributions from pasture sources are disproportionate to the spatial coverage in each individual sub-catchment (Figure 8.15). This indicates that additional factors can also control sediment mobilisation and delivery from the pasture source category (Collins *et al*., 2010b). These factors could include the connectivity between pasture fields and the river channel network, including the spatial arrangement of watering points (Motha *et al*., 2004), along with livestock stocking densities and the severity of associated surface soil poaching in particular sub-catchments.

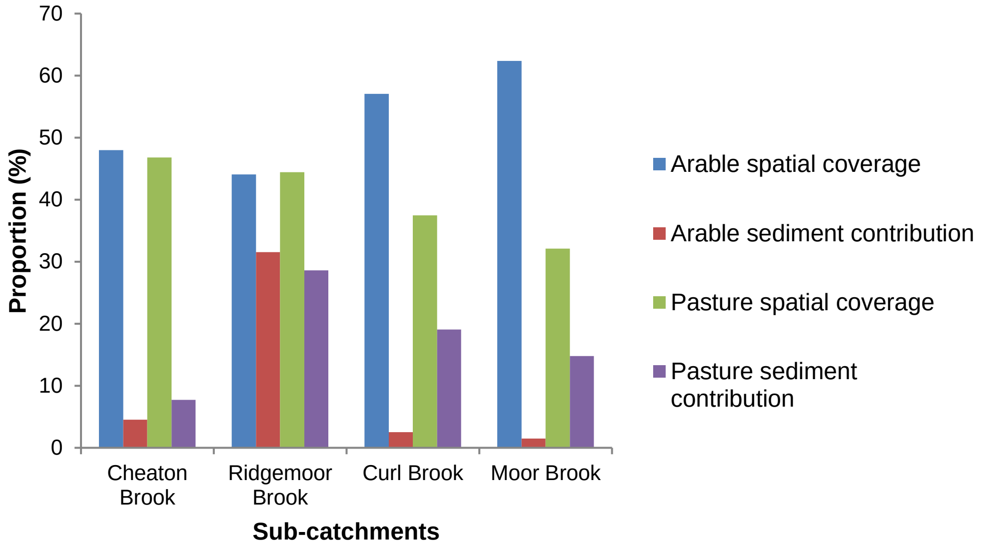

Figure 8.15 The proportion of land area occupied by pasture and arable surfaces and the relative sediment contributions from each sub-catchment.

Sediment mobilisation and delivery from grazed surface soils could be controlled by the connectivity between pasture fields and the channel network within a particular sub-catchment. Figure 8.7 shows that pasture fields are directly connected to the channel network in all four catchments, with a greater number of field parcels adjacent to the watercourse in the Cheaton and Ridgemoor Brook sub-catchments. More than half of all fields directly connected to the watercourse in these two sub-catchments are utilised for grazing, yet whilst this source type is the second most dominant source of sediment in the Ridgemoor Brook sub-catchment, sediment contributions from grazed surface soils are relatively low in the Cheaton Brook. Factors affecting connectivity between grassland surfaces and the channel network within a particular sub-catchment could also control variations in sediment mobilisation and delivery from this source category. According to Motha *et al.* (2004), sediment contributions from grazed surfaces can be influenced by the spatial arrangement of watering points and the location of stock-tracks. Field reconnaissance highlighted the frequent occurrence of watering points and cattle stock-tracks in the Ridgemoor, Curl and Moor Brook sub-catchments. Stocking-tracks regularly converged towards and through the channel, which promoted high runoff and substantial erosion potential. The associated heavily poached surface soils were therefore vulnerable to subsequent mobilisation and offered direct connectivity to the channel network (Figure 8.16). This effectively enhances sediment delivery to the channel network, which reflects the significant contributions from the pasture source category to the total suspended sediment collected in these sub-catchments. In contrast, occurrences of watering points were limited in the Cheaton Brook sub-catchment and there were only a few instances of direct connectivity between stock-tracks and the channel network. As a result, it was evident that poaching and subsequent sediment mobilisation was less severe, effectively limiting sediment delivery to the channel. This reflects the relatively low contribution from the pasture source category to the suspended sediment collected in this sub-catchment.

Figure 8.16 Watering points and cattle stock-tracks offering direct connectivity to the channel network in the Ridgemoor, Curl and Moor Brook sub-catchments.

Livestock type and stocking densities within particular sub-catchments could also control variations in sediment mobilisation and delivery from this source category, which would conceal the sediment associated effects of increases in spatial coverage (Collins *et al*., 2010b). It was apparent throughout field reconnaissance that pasture fields located in the lower and middle reaches of the Cheaton Brook sub-catchment were generally exploited for sheep grazing. As a result, surface soils were susceptible to compaction and subsequent sediment runoff was restricted to heavy rainfall events (Figure 8.17). In contrast, although sheep grazing was also observed in the Ridgemoor, Curl and Moor Brook sub-catchments, pasture fields adjacent to the channel network were more frequently used for cattle grazing. Livestock pressure was concentrated in the riparian zones (Trimble and Mendel, 1995), leading to intensive poaching of the surface soils, which was particularly severe in gateways and around feeder ring areas (Collins and Walling, 2007; Collins *et al*., 2012b). These disturbed surfaces typically create a significant supply of loose erodible material and generate widespread surface runoff which subsequently routes mobilised sediment to the channel network (Betteridge *et al.,* 1999; Motha *et al.,* 2004; Walling *et al*., 2008). Consequently, extensive fine sediment mobilisation and delivery was evidently more severe within the Ridgemoor, Curl and Moor Brook sub-catchments (Figure 8.18). Accordingly, sediment contributions from the pasture source category to the total suspended sediment collected in these three sub-catchments are greater than the contribution predicted in the Cheaton Brook sub-catchment, where surface degradation and poaching associated with sheep grazing is not as intensive.

Figure 8.17 Examples of surface soil compaction and fine sediment runoff caused by sheep grazing in the Cheaton Brook sub-catchment.

Figure 8.18 Examples of severe poaching and sediment mobilisation associated with cattle grazing in the Ridgemoor Brook, Curl Brook and Moor Brook sub-catchments.

However, although it was evident that pasture fields in the Cheaton Brook sub-catchment were primarily used for sheep grazing, intensive cattle grazing, and associated poaching of the surface soils were also observed on pasture fields adjacent to small tributaries in the upper parts of the sub-catchment (Figure 8.19). Nevertheless, the apportionment results indicate that these areas do not have a significant impact on the contributions from this specific source category, which could reflect the nature of the channel network. The locality and low velocities associated with these small tributaries suggest that the mobilised sediment is less likely to be transferred to the main-stem channel and as a result is unlikely to have an impact on the sediment system at the sub-catchment outlet.

Figure 8.19 Examples of intensive surface soil poaching on pasture fields in the upper parts of the Cheaton Brook sub-catchment.

Variations in the relative importance of pasture sources are consistent with the results obtained for several other catchments in the UK using the fingerprinting approach. Contributions were estimated to range between 2% and 25% for a number of sub-catchments within the Wye, with particular contributions of 9% and 14% for two sub-catchments located within the Lugg (Walling *et al.,* 2008). Gruszowski *et al.* (2003) also reported contributions of 14% in the neighbouring River Leadon catchment, and contributions of 12-16% were estimated from this source category in the Hampshire Avon catchment (Heywood, 2002). These estimates are all consistent with the contributions reported in this study for the Cheaton, Curl and Moor Brook sub-catchments. Haley (2010) demonstrated that pasture sources were significant in the River Arrow catchment, with contributions estimated at 31%, which is consistent with the contribution estimated for the Ridgemoor Brook sub-catchment (29%) in this study. Other studies have reported more significant contributions from this source category. Pasture sources contributed 72% and 65% of the total suspended sediment in the Exe and Severn catchments respectively (Collins *et al.,* 1997a), whereas pasture contributions ranged between 42% and 75% for distinct sub-catchments in the Yorkshire Ouse (Walling *et al.,* 1999b). However, the dominance of pasture in the landscape of these specific catchments justifies its significance.

8.2.4 Channel Banks

It is evident from Figure 8.2 that channel banks also represented an important source of suspended sediment in each of the four sub-catchments. Although the relative channel bank contribution from each sub-catchment is of a similar magnitude (ranging between 18% and 22%), it is apparent that channel bank erosion has a greater influence on total suspended sediment in the Ridgemoor Brook sub-catchment. Catchment size can exert a significant influence on the extent of channel bank contributions in that values for the large catchments are generally greater than those for the smaller catchments (Walling and Collins, 2005; Janes *et al*., 2017). However, when considering the area of the four sub-catchments in relation to the associated channel bank contributions it is perhaps a little surprising that this relationship is not observed (Figure 8.20). Cheaton Brook has the largest catchment area of 39 km^2, yet the load-weighted mean channel bank contribution of 19% is relatively low. In contrast, Moor Brook has the smallest catchment area of 4 km^2 and whilst the lowest channel bank contribution (18%) is associated with this sub-catchment, the proportion of sediment predicted by the mixing model is relatively high. This indicates that factors in addition to catchment size control differences in the relative importance of channel bank sources. These could include (i) contrasts in the particle size of the actively eroded material; (ii) channel morphology, dimensions of the actively eroding bank walls and the discharge response of the catchment; and (iii) riparian land use pressures including trampling and degradation of the channel margins by livestock (Walling *et al*., 2002; Walling, 2005; Collins *et al.,* 2010b).

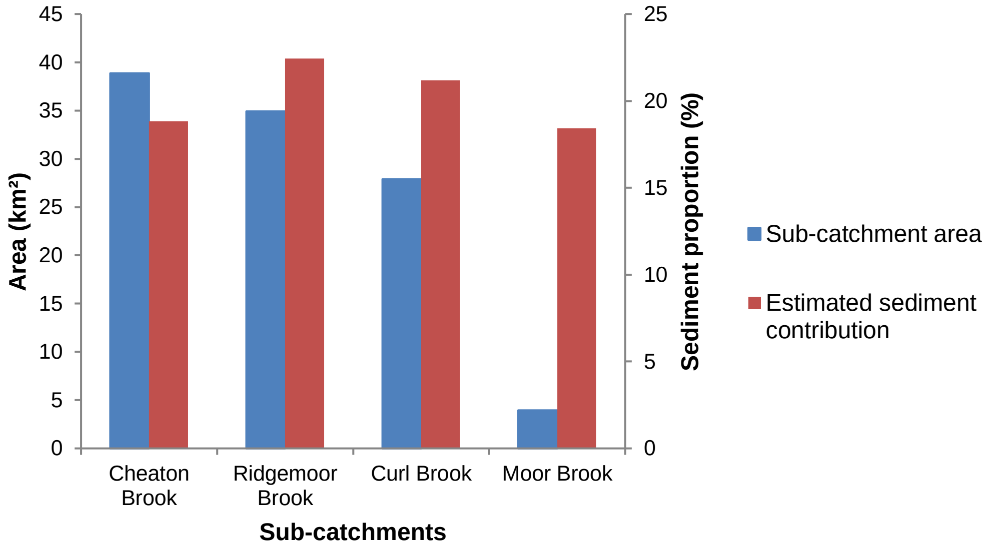

Figure 8.20 Catchment size and the associated relative contributions from channel bank sources from each sub-catchment.

Variations in sediment mobilisation and delivery from channel banks sources in individual sub-catchments could be controlled by the particle size of the actively eroded material. Couper (2003) reported that riverbanks with high silt-clay contents were more resistant to fluvial erosion than those of lower silt-clay contents. Particle size characteristics of the channel bank material can also be put into context with the catchment scale results (see Chapter 4, section 4.3). It is evident that the suspended sediment collected at the Eaton monitoring site immediately downstream of the Cheaton and Ridgemoor Brook sub-catchments is slightly finer than the sediment collected at the Broadward site downstream of the Curl and Moor Brook sub-catchments (Table 4.4). This is reflected in the relative sediment contributions from channel bank sources. Contributions range from 19 to 22% in the Cheaton and Ridgemoor Brook, whilst contributions range between 18% in the Moor Brook to 21% in the Curl Brook sub-catchment.

When considering the average silt-clay content of the channel bank source material collected in relation to the associated channel bank contributions, it is evident that this relationship is not observed in all sub-catchments (Figure 8.21). The channel bank material in all four sub-catchments contains high silt-clay contents (82-95%) suggesting that the riverbanks are relatively resistant to fluvial erosion. Channel banks in the Moor Brook sub-catchment have with the highest silt-clay contents (95%) and are also associated with the lowest sediment contributions from this source type. Furthermore, the mean particle size of channel bank material is finest in this sub-catchment with a d_{50} value of 10.7 µm. However, this relationship is not observed in the Ridgemoor Brook sub-catchment. Contributions from channel bank material are greatest in the Ridgemoor Brook, yet the channel bank material in this sub-catchment is also characterised by a high silt-clay content and a mean d_{50} particle size of 17.2 µm (Figure 8.21). Therefore, this suggests that additional factors could control variations in the relative importance of channel bank sources.

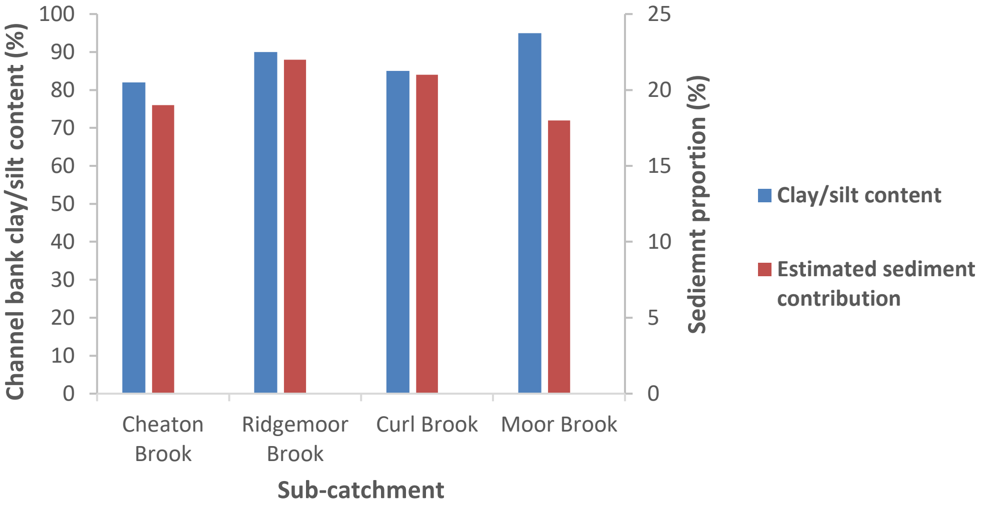

Figure 8.21 Clay/silt content of the channel bank material and the associated relative contributions from channel bank source from each sub-catchment.

Variations in sediment mobilisation and delivery from channel bank sources could be controlled by channel morphology, river bank dimensions and the discharge response of a particular sub-catchment, which would conceal the sediment associated effects of increases in catchment size. The importance of discharge and channel bank stability in controlling the detachment and entrainment of bank material has been recognised in other sediment fingerprinting studies (Walling *et al.,* 1999b; Owens *et al*., 2000; Heywood, 2002). It was apparent throughout field reconnaissance that channel banks in the Moor Brook sub-catchment were generally lower, relatively stable and better vegetated than channel banks in the other three sub-catchments. This, coupled with insignificant channel density and the low energy nature of the river especially during storm runoff events, implies that the bank profiles in this particular sub-catchment are less susceptible to erosion (Figure 8.22). Furthermore, the topography of this sub-catchment is likely to control sediment mobilisation from channel bank material. Moor Brook is characterised by low relief (Figure 8.5) and as a result, smaller sediment contributions from channel bank sources are predicted from the mixing model in the Moor Brook sub-catchment (Walling *et al.,* 2008). In contrast, there are a high number of steep, well-developed and relatively unstable actively eroding channel banks located on the main river in the Ridgemoor, Curl and Cheaton Brook sub-catchments, which are characterised by high elevation in the upper parts of the catchment (Figure 8.5). The greater channel densities associated with these sub-catchments and the intensive stream energy during storm runoff events encourage elevated rates of natural bank erosion through widespread undercutting and excessive slumping (Figure 8.23). Subsequently, this source material is directly delivered to the channel network through hydraulic processes and reflected in the slightly greater contributions from channel bank sources predicted for in these three sub-catchments.

Figure 8.22 Examples of the small, well-vegetated channel banks which are less susceptible to erosion in the Moor Brook sub-catchment.

Nevertheless, it was evident throughout field reconnaissance that the greatest stream energy was associated with the Cheaton Brook sub-catchment, generating the highest instantaneous suspended sediment loads. In addition, bank slumping in the mid and lower parts of the sub-catchment appeared to be more extensive (Figure 8.24). Yet despite this, it is surprising that the contribution from channel bank sources is relatively low when compared with the channel bank contributions in the other sub-catchments. This indicates that additional factors could control variations in the relative importance of channel bank sources.

Figure 8.23 Examples of actively eroding channel banks promoting direct delivery of source material to the river network in the Ridgemoor Brook, Curl Brook and Cheaton Brook sub-catchments.

Figure 8.24 Examples of severe channel bank erosion and slumping in the mid and lower parts of the Cheaton Brook sub-catchment.

Channel bank sources are often unrepresented in sediment fingerprinting studies. Most studies characterise channel bank material as a mixture of sediment derived from fluvial erosion of channel margins and from particular land management practices causing aggravated bank erosion. The latter, which is commonly associated with disturbances by grazing animals, is likely to accelerate sediment mobilisation and delivery from this source type. This is highlighted by Collins *et al.* (2013b) who reported a significant difference between sediment contributions from fluvially eroded and poached channel margins. For example, sediment contributions from fluvially eroded channel margins ranged between 1 and 3%, whereas sediment contributions from poached channel margins were significantly higher (19-47%). Therefore, riparian land use pressures, including trampling and degradation of the channel margins by livestock, could act as an additional control on the variations in the relative importance of channel bank sources within particular sub-catchments.

In areas with relatively high stocking densities, increased sediment mobilisation from channel bank sources is more likely to reflect the trampling and degradation caused by livestock, as opposed to natural erosion of the steep well-formed banks (Walling and Collins, 2005; Collins *et al*., 2012a). Therefore, it is not unexpected that the greatest contributions from channel bank sources are associated with sub-catchments with the highest pasture contributions, albeit without the associated differences in magnitude (Figure 8.1). Field reconnaissance in the Ridgemoor and Curl Brook sub-catchments particularly demonstrated the widespread occurrence of channel bank degradation through severe trampling by livestock, with cattle ramps frequently evident (Figure 8.25). By generating higher velocities and greater turbulence (Trimble, 1994; Trimble and Mendel, 1995), cattle ramps can intensify the shear stress on bank walls, enhancing bank erosion and thereby amplifying sediment delivery (Collins *et al.,* 2010a). The impact of riparian grazing and uncontrolled access to the channel network on channel bank sources has also been demonstrated by other fingerprinting studies (Owens *et al.,* 2000; Walling, 2005; Collins and Walling, 2007; Collins *et al*., 2010a; 2012a). In contrast, channel bank degradation by livestock trampling was less frequently observed in the Cheaton and Moor Brook sub-catchments. As a result, sediment contributions from channel bank sources in these two sub-catchments are likely to reflect contributions from fluvially eroded channel margins and are slightly lower than the predicted contributions in the Ridgemoor and Curl Brook sub-catchments. Nevertheless, differences in channel bank contributions from sub-catchments where land management practices cause exaggerated bank erosion and sub-catchments where fluvial erosion of channel margins is common are not significant. This suggests that a combination of factors discussed control sediment mobilisation and delivery from channel bank sources.

Figure 8.25 Examples of bank degradation and erosion in the Ridgemoor Brook and Curl Brook sub-catchments as a result of severe livestock trampling.

Although channel banks represent an important source of fine sediment in all four sub-catchments, the contributions are below those obtained by several other fingerprinting studies undertaken in agricultural catchments in the UK. Channel bank contributions were estimated to range between 40% and 53% for a number of sub-catchments in the Wye, with particular contributions of 48% and 43% for two sub-catchments located within the Lugg (Walling *et al.,* 2008). This is consistent with the 42% predicted by Walling *et al*. (2003) during a reconnaissance survey on sediment provenance in the Wye catchment. Collins (2008) also reported channel bank sediment contributions ranging between 41% and 66% in the River Sem sub-catchment of the Hampshire Avon, and contributions of 32% were estimated from this source category in the Arrow catchment (Haley, 2010). However, a significant proportion of the channel bank contributions in agricultural catchments are likely to reflect the supply of sub-surface material to the channel from incised farm tracks (Collins *et al*., 2012a). Since the sampling procedures in these past studies amalgamated channel bank and subsurface sources, channel bank contributions may potentially be amplified. Although the channel bank contributions in all four sub-catchments could be perceived as rather low, they are in reasonable agreement with other fingerprinting studies where farm tracks were classified as an individual source type. Owing to farm tracks being a significant source of fine sediment, channel bank sources were subsequently reported to contribute between 16% and 40% of the suspended sediment in the Upper Kennet catchment (Collins *et al.,* 2012a) and between 23% and 32% for a sub-catchment in the Upper Piddle catchment (Collins *et al*., 2010c). Alternative studies, which classified additional subsurface sources independent of channel bank sources, including subsoils in the neighbouring Leadon catchment (Gruszowski *et al*., 2003) and field drains in the Lugg catchment (Russell *et al.,* 2001), generated smaller channel bank contributions of 8% and 12% respectively. Therefore, this indicates that the channel bank contributions generated from the mixing models in the four sub-catchments are relatively consistent with other fingerprinting studies, which distinguish between channel banks and additional subsurface sources. They are also consistent with other studies that overlook subsurface sources completely and only incorporate channel bank sources in the sampling procedure. Such studies (for example, Walling *et al*., 1993; Walling and Woodward, 1995), have reported bank contributions to the overall suspended sediment load of 12-21%.

8.2.5 Woodland

Figure 8.2 also demonstrates that there is a large variation in the contribution of woodland sources to the suspended sediment collected at the outlets of the two sub-catchments where this source type was included in the fingerprinting process. It is apparent that the influence of woodland topsoils on total suspended sediment in the Curl Brook sub-catchment is insignificant, with contributions of only 2%. In contrast, surface erosion from woodland topsoils represented the second most dominant source of fine sediment in the Cheaton Brook sub-catchment, contributing 21% of the total suspended sediment. It has been acknowledged in previous fingerprinting studies that the sediment contribution from woodland sources reflects the proportion of the specific catchment occupied by woodland areas (Walling *et al.,* 1999b; Owens *et al*., 2000; Heywood, 2002; Walling, 2005). In catchments where the spatial extent of woodland is large, associated sediment contributions have been reported to range between 22% and 77% (Collins *et al*., 1997b; 1997c; Motha *et al.,* 2003), far greater than the contributions from woodland sources in catchments with limited spatial coverage. However, though the areal extent of woodland within the Curl and Cheaton Brook sub-catchments is equivalent (5%) and limited, Cheaton Brook shows a higher contribution of sediment from this source type (Figure 8.26). Therefore, variables other than proportion of woodland are potentially active.

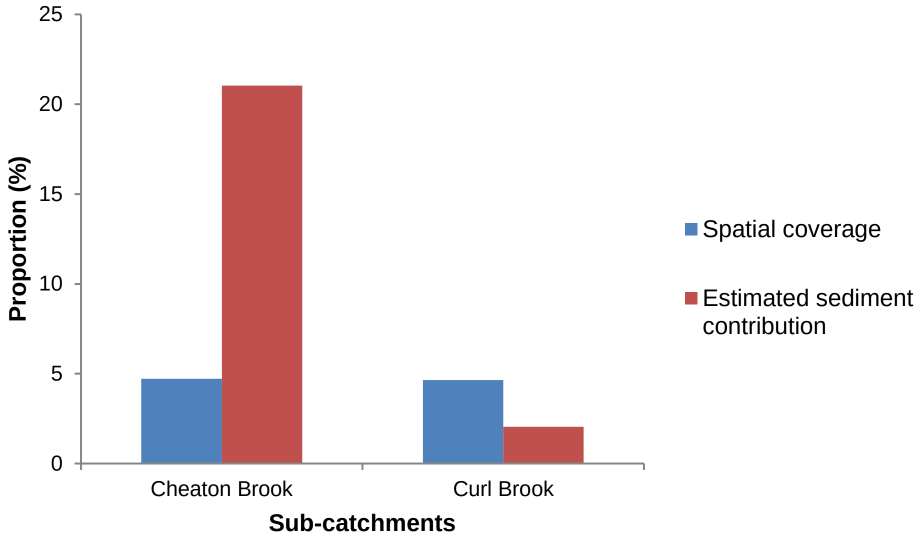

Figure 8.26 The proportion of land area occupied by woodland surfaces and the associated relative sediment contributions from each sub-catchment.

The level of surface erosion and related sediment mobilisation and delivery commonly associated with areas of woodland varied between the Curl and Cheaton Brook sub-catchments (Morgan, 1986). When considering the connectivity between woodland surface soils and the channel network (Figure 8.7) it is evident that large areas of woodland are located adjacent to the watercourse in the middle parts of the Cheaton Brook sub-catchment. This reflects the relatively large contribution from the woodland source category to the suspended sediment collected in this sub-catchment. Although the area of woodland directly connected to the river network in the Curl Brook sub-catchment is similar to that in the Cheaton Brook, the areas are more interspersed and refined mainly to the peripheries of the catchment (Figure 8.7).

Furthermore, field reconnaissance showed that woodland areas in the Curl Brook were more established and had a greater vegetation cover density and organic litter layer (Figure 8.27), which would limit the erodibility of topsoils, and restrict associated surface runoff (Collins *et al*., 1997c; Walling and Collins, 2005; Collins and Walling, 2007). This is consistent with the findings of other fingerprinting studies in agricultural catchments in the UK (e.g. Collins *et al*., 1997a; Walling *et al.,* 1999b; Walling, 2005; Collins and Walling, 2007; Walling *et al*., 2008), which have reported contributions from woodland sources ranging between 0% and 7%. The woodland areas adjacent to the river network in the Cheaton Brook sub-catchment were less developed and resembled relatively immature plantations, with limited undergrowth and vegetation cover (Figure 8.28). The bare soils are more exposed to erosion and surface runoff, enhancing the probability of contributing to sediment pollution within the sub-catchment (Clark, 2009). Further, field reconnaissance in this sub-catchment demonstrated that even within the infrequent well-established woodlands, steep-sided slopes and soft soils exaggerated surface runoff during heavy rainfall events. Accordingly, relative sediment contributions derived from woodland sources are much more significant in this sub-catchment. This is consistent with the findings of a recent study in the River Arrow catchment (Haley, 2010), where past clear felling and replanting has led to an increase in immature plantations. Although mean contributions of 6% were reported since the 1980s, woodland sources contributed an “uncharacteristic” 15% in the latter part of the study, which is in reasonable agreement with the 21% predicted in the Cheaton Brook sub-catchment. In addition, Burke (2011) reported relative sediment contributions of 14% from woodland sources in the Lugg catchment, which also corresponds closely with the woodland contribution in this sub-catchment.

Figure 8.27 Examples of woodland areas with extensive vegetation cover and litter layer, limiting surface runoff in the Curl Brook sub-catchment.

Figure 8.28 Examples of immature plantations adjacent to the channel network with visible surface runoff in the Cheaton Brook sub-catchment.

8.2.6 Summary

Whilst the load-weighted mean source contributions are generally consistent with the findings of other sediment fingerprinting studies in agricultural catchments, comparisons between the relative significance of different source types and land use data suggest that spatial coverage does not fully control sediment mobilisation and delivery. As a result, spatial extent does not entirely account for the variations in relative sediment contributions illustrated in Figure 8.2. Although it is expected that dominant sediment contributors would reflect, at least in part, the prevailing land use characteristics and size of a particular catchment (Collins *et al.,* 2010b), the application of the sediment source fingerprinting technique has illustrated a more nuanced situation with some disproportionate sediment contributions derived from arable, pasture and farm track surface sources. Temporal fluctuations in relative contributions from sources are a further variable and are considered in the next sub-section.

8.3 Temporal Variation

The load-weighted mean relative sediment contributions for each sub-catchment, presented in Table 8.1, are likely to conceal significant inter-storm variability in the contribution of the individual source groups (Russell *et al.,* 2001). The sediment source apportionment and associated RME for individual sampling periods from each sub-catchment is presented in Tables 8.2 – 8.5. The RME for the majority of samples is below 15% enabling the mixing models to provide an acceptable prediction of sediment provenance (see Collins and Walling, 2000). However, there are a few notable exceptions and as such interpretations upon these intervals should be cautious.

Table 8.2 Sediment source apportionment results and associated RME for each suspended sediment sample in the Cheaton Brook sub-catchment.

Sampling period	Estimated sediment contribution (%)					RME (%)
	Pasture	Arable	Channel banks	Woodland	Farm tracks	
1. 29/03/12-17/05/12	24	0	2	0	74	3.1
2. 17/05/12-14/06/12	3	0	5	0	92	7.5
3. 14/06/12-06/07/12	11	12	20	7	50	1.0
4. 06/07/12-13/07/12	0	7	29	28	36	5.7
5. 13/07/12-08/08/12	0	0	3	49	48	9.0
6. 08/08/12-04/09/12	0	0	6	27	67	12.5
7. 04/09/12-01/10/12	37	0	6	32	25	2.3
8. 01/10/12-24/10/12	15	0	3	12	70	9.6
9. 24/10/12-13/11/12	58	0	2	26	14	27.4*****

** RME value above 15% so sample should be interpreted with some caution.*

Table 8.3 Sediment source apportionment results and associated RME for each suspended sediment sample in the Ridgemoor Brook sub-catchment.

Sampling period	Estimated sediment contribution (%)				RME (%)
	Pasture	Arable	Channel banks	Farm tracks	
1. 29/03/12-17/05/12	31	64	0	5	3.7
2. 17/05/12-14/06/12	36	44	0	20	16.8*
3. 14/06/12-06/07/12	7	31	37	25	0.8
4. 06/07/12-08/08/12	8	0	61	31	2.2
5. 08/08/12-04/09/12	8	34	44	14	14.4
6. 04/09/12-01/10/12	57	17	0	26	5.3
7. 01/10/12-24/10/12	45	53	0	2	2.3
8. 24/10/12-13/11/12	76	12	7	5	9.6
** RME value above 15% so sample should be interpreted with some caution.*					

Table 8.4 Sediment source apportionment results and associated RME for each suspended sediment sample in the Curl Brook sub-catchment.

Sampling period	Estimated sediment contribution (%)					RME (%)
	Pasture	Arable	Channel banks	Woodland	Farm tracks	
1. 29/03/12-17/05/12	27	0	11	0	62	0.2
2. 17/05/12-14/06/12	0	0	18	0	82	7.2
3. 14/06/12-06/07/12	22	0	23	0	44	5.2
4. 06/07/12-13/07/12	0	0	37	0	63	0.9
5. 13/07/12-08/08/12	24	0	12	0	64	1.7
6. 08/08/12-04/09/12	25	0	27	0	48	7.2
7. 04/09/12-01/10/12	11	0	16	0	73	12.3
8. 01/10/12-24/10/12	50	18	12	0	20	34.5*
9. 24/10/12-13/11/12	9	0	14	22	55	15.5
** RME value above 15% so sample should be interpreted with some caution.*						

Table 8.5 Sediment source apportionment results and associated RME for each suspended sediment sample in the Moor Brook sub-catchment.

Sampling period	Estimated sediment contribution (%)				RME (%)
	Pasture	Arable	Channel banks	Farm tracks	
1. 29/03/12-17/05/12	21	0	39	40	15.8
2. 17/05/12-14/06/12	10	0	0	90	30.5*
3. 14/06/12-06/07/12	24	0	27	49	3.0
4. 06/07/12-13/07/12	10	0	2	88	7.7
5. 13/07/12-08/08/12	13	0	0	87	8.5
6. 08/08/12-04/09/12	32	0	0	68	24.7*
7. 04/09/12-01/10/12	31	0	46	23	13.6
8. 01/10/12-24/10/12	2	2	32	64	19.4*
9. 24/10/12-13/11/12	2	17	0	81	3.5

** RME value above 15% so sample should be interpreted with some caution.*

Figure 8.29 illustrates the relative sediment contributions of the different source types to the sediment samples collected from individual flood events in each sub-catchment. For the purpose of interpretation, these apportionment results are also compared with rainfall intensity data for each sampling period. It is evident that distinct temporal variability is observed in the origins of the sediment loads transported through each sub-catchment outlet over the period of study. However, as the mixing models do not account for sediment transit times, it is important to recognise that these temporal contributions relate to the suspended sediment passing the catchment outlet during individual events, rather than its original mobilisation within the particular sub-catchment (Walling *et al.,* 2008). It is possible that sediment mobilised from a particular source and transferred to the channel during one flood event may become stored within the channel for a period of time, then remobilised and transported to the catchment outlet during another flood event (Svendsen and Kronvang, 1995).

In the case of the Cheaton Brook sub-catchment (Figure 8.29a) sediment contributions from farm track surfaces exhibited the greatest temporal variations, ranging from as little as 14% (sampling period 9), to a peak contribution of 92% (sampling period 2). It is evident that this source type represented the dominant source of fine sediment throughout the majority of storm events, except sampling periods 7 and 9 where pasture topsoils dominated with respective contributions of 37% and 58%. The corresponding minimum contribution from pasture topsoils was zero, or so low that it was not recognised by the mixing model, throughout sampling periods 4, 5 and 6. Sediment contributions from woodland surface soils also showed substantial variation, with minimum contributions of zero (sampling periods 1 and 2) and a maximum contribution of 49% during sampling period 5. Supplies from channel bank sources displayed less variability, with minimum contributions of 2% (sampling periods 1 and 9) and a maximum contribution of 29% (sampling period 4). It is apparent that the least significant source of fine sediment was arable topsoils, which did not contribute any sediment throughout most storm events with the exception of sampling periods 3 and 4 where relative contributions were predicted at 12% and 7% respectively.

In contrast, more distinct inter-storm variability is observed for the relative contributions from each source type in the Ridgemoor Brook sub-catchment (Figure 8.29b). Pasture surface sources displayed the widest range of relative sediment contributions, ranging from as low as 7% (sampling period 3) to a peak of 76% (sampling period 8). Sediment contributions from arable topsoils also revealed large temporal variations, with a minimum contribution of zero during sampling period 4, and a maximum contribution of 64% during sampling period 1. It is apparent that channel bank sources only contributed sediment throughout four of the eight sampling periods, within which a minimum contribution of 7% (sampling period 8) and maximum contribution of 61% (sampling period 4) was observed. Farm track surfaces displayed the least significant temporal variations within this sub-catchment, with sediment contributions ranging from a low of 2% during sampling period 2, to a peak of 31% during sampling period 4.

In comparison, sediment contributions from farm track surfaces demonstrated the largest temporal variations in the Curl Brook sub-catchment (Figure 8.29c), with contributions ranging from a minimum of 20% (sampling period 8) to a maximum of 82% during sampling period 2. Similar to the Cheaton Brook sub-catchment, it is evident that this source type represented the dominant source of fine sediment during every storm event, with the exception of sampling period 8, where pasture topsoils dominated with a maximum contribution of 50%. The corresponding minimum contribution from pasture surface sources was zero, or so low that it was not recognised by the mixing model throughout sampling periods 2 and 4. Sediment contributions from channel bank sources also demonstrated important variations between individual storm events, with a minimum contribution of 11% (sampling period 1) and a peak contribution of 37% (sampling period 4). It is apparent that the least significant sources of fine sediment were arable and woodland surface soils, which only contributed sediment during one different storm event. Relative sediment contributions were predicted at 18% during sampling period 8 and 22% throughout sampling period 9 respectively.

Similarly, in the Moor Brook sub-catchment (Figure 8.29d) farm track surfaces revealed the greatest temporal variation, with contributions ranging from 23% (sampling period 7) to as much as 90% (sampling period 2). This source type represented the dominant source of fine sediment during every storm event, with the exception of sampling period 7, where channel bank sources dominated with a maximum contribution of 46%. Channel bank sources only contributed sediment throughout another four sampling periods, within which the corresponding minimum contribution was 2%. Sediment contributions from pasture surfaces also demonstrated important variations, with minimum contributions as low as 2% during sampling periods 8 and 9, and a maximum contribution of 32% (sampling period 6). The least significant source of fine sediment was arable topsoils which, similar to the Cheaton Brook and Curl Brook sub-catchments, failed to contribute any sediment throughout most storm events, with the exception of sampling periods 8 and 9, where relative contributions were predicted at 2% and 17% respectively.

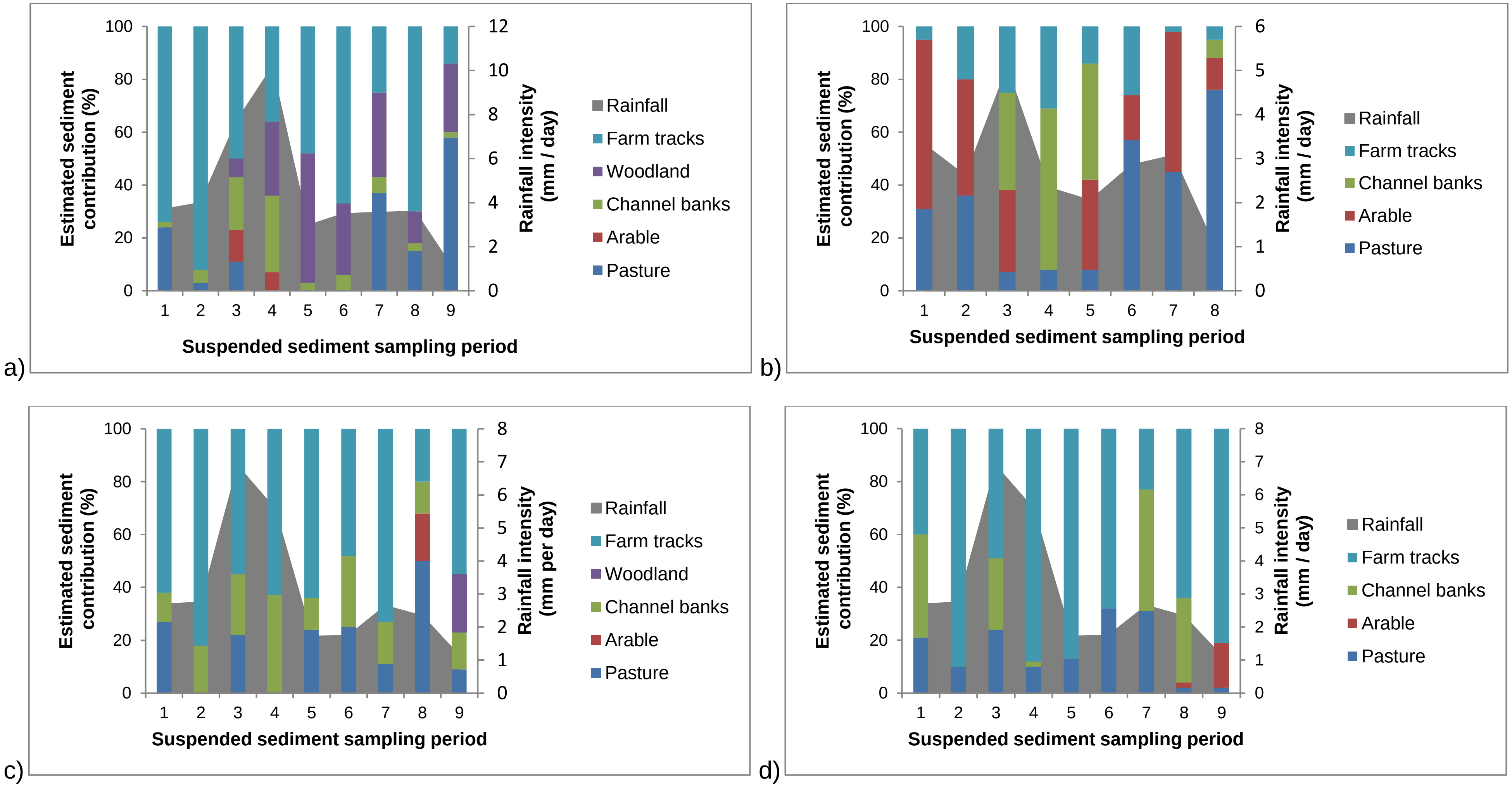

Figure 8.29 Temporal variations in relative sediment contributions and rainfall intensity associated with each sampling period between March and November 2012 for a) Cheaton Brook, b) Ridgemoor Brook, c) Curl Brook and d) Moor Brook.

8.3.1 Arable

The complex temporal variations illustrated in Figure 8.20 are likely to reflect a number of controls including inter-storm variations in the magnitude and intensity of precipitation and its spatial distribution, variations in land use activities and land cover and the timing of sample collection relative to the delivery of material mobilised from different sources during storm events (Collins *et al.,* 1997c; Walling *et al.,* 1999b; Collins *et al.,* 2001). Variations in land use activities and land cover within the Lugg catchment (see Table 6.4) represent an important control determining the relative importance of source type. In most cases, arable topsoils generally represented a more significant source of fine sediment during the autumn and early spring months (October - March), when such surfaces are bare or sparsely covered by crops and thus susceptible to water erosion (Collins and Walling, 2007; Walling *et al.,* 2008). Arable surface contributions in the Curl Brook and Moor Brook sub-catchments were isolated to one or two individual storm events throughout the autumn period (October – November). These contributions, which ranged between 2% and 18%, coincided with and immediately succeeded harvesting activities within the catchment, which leave soil in a condition highly susceptible to erosion (Rasmussen, 1999). This was particularly evident following potato harvesting, where soils become compact reducing the porosity, limiting water infiltration and subsequently increasing sediment runoff (Figure 8.30). In the case of the Ridgemoor Brook sub-catchment, arable contributions were more consistent throughout the whole sampling period, indicating that sediment mobilisation and delivery from this source category is not just restricted to particular land use activities. However, the more significant contributions of 64% and 53% were evident during two different storm events, which respectively occurred during soil preparation activities in the form of tillage for spring sowing (March) and the harvesting period (October).

Figure 8.30 Arable fields following potato harvesting within the Lugg catchment (2nd November 2012).

Nevertheless, this ‘seasonal’ pattern in arable contributions was not consistent with the apportionment results for the Cheaton Brook sub-catchment. Arable surface contributions were isolated to two individual storm events occurring between June and July, when such surfaces are usually densely covered by crops. These contributions, which ranged between 7% and 12%, did not coincide with any major land use activities within the catchment. This indicates that factors in addition to land use activities and land cover are likely to control variations in arable contributions in this sub-catchment. When considering the magnitude and intensity of precipitation throughout individual sampling periods, it is evident that arable contributions in the Cheaton Brook sub-catchment only coincide with sampling periods of high intensity rainfall (Figure 8.29a). High intensity storm events during the two sampling periods, which coincided with the wettest April-June on record (Met Office, 2012), saturated the easily erodible fine sandy soils in the catchment and dramatically increased sediment runoff (Figure 8.31). This was especially noticeable for arable surface soils, where the specific land use practices had reduced infiltration capacity and readily created pathways for enhanced sediment transport (Theurer *et al.,* 1998).

Figure 8.31 Examples of soil saturation and sediment runoff from arable surfaces during intense rainfall within the Lugg catchment (28th June 2012).

8.3.2 Channel Banks

It is also evident that channel bank contributions are generally greater during periods of more intensive rainfall, when higher energy and larger discharge events are likely to significantly increase the detachment and entrainment of channel bank material (Walling *et al.,* 1999b; Owens *et al.,* 2000; Collins, 2008). In the Cheaton Brook sub-catchment, significant channel bank contributions were isolated to two extreme high intensity rainfall events occurring between June and July (Figure 8.29a). During these two sampling periods, contributions from channel bank sources ranged between 20% and 29%, whereas equivalent contributions for the remaining sampling periods with less intense rainfall did not exceed 6%. This indicates that variations in the magnitude and intensity of precipitation can control variations in contributions from channel bank sources in this sub-catchment. Although the temporal variations in channel bank contributions are not as pronounced in the Curl Brook sub-catchment, it is clear that a relationship also exists between rainfall intensity and sediment contributions from channel bank sources (Figure 8.29c). As in the case of the Cheaton Brook sub-catchment, the most significant channel bank contributions (23% and 37%) coincided with periods of high intensity rainfall during June and July. However, the relatively large contribution of 27% evident in sampling period 6 (August – September) when rainfall intensity was not particularly high, does not conform to this pattern. Other catchment pressures, involving livestock trampling of the channel margins and subsequent channel bank degradation could account for this ‘irregular’ contribution.

In the case of the Ridgemoor Brook sub-catchment, channel banks only represented a significant source of fine sediment in sampling periods during the summer months (June – August). During these three sampling periods, contributions from channel bank sources ranged between 37% and 61%, whereas equivalent contributions for the remaining sampling periods were much less significant, with a maximum contribution of only 7%. This ‘seasonal’ pattern is consistent with the apportionment results in two Wye sub-catchments where highly significant channel bank contributions of 71-93% were attributed to low sediment fluxes and reduced contributions from surface sources during the summer months (Walling *et al.,* 2008). However, when considering the magnitude and intensity of precipitation throughout individual sampling periods, it is evident that the significant channel bank contributions in the Ridgemoor Brook sub-catchment coincide with, and shortly after, sampling periods of high intensity rainfall (Figure 8.29b). The initial period of significant channel bank contributions (between June and July) coincided with the highest intensity rainfall. Nevertheless, the more substantial channel bank contributions seem to occur in the two succeeding sampling periods with less intense rainfall. This could reflect channel bank destabilisation and collapse during the initial high intensity storm event, which was then followed by a period of sediment flushing throughout the subsequent smaller events. In addition, the preferential deposition of coarser sediment (Phillips and Walling, 1999; Heywood, 2002), which predominantly originated from channel bank sources in this sub-catchment, suggests that the associated sediment transit times are likely to be particularly large. As a result, it is probable that some sediment is stored within the channel and transported to the sub-catchment outlet during the following events. Therefore, it is more likely that the variations in channel bank contributions within this sub-catchment are the result of inter-storm variations in the magnitude and intensity of precipitation, rather than any distinct seasonal patterns.

8.3.3 Pasture

In general, pasture topsoils represented a more significant source of fine sediment during the autumn period (September – November) when such surfaces, which are characterised by high soil moisture content and frequent waterlogging, are highly susceptible to severe poaching by high livestock densities (Evans, 1997; Pietola *et al.,* 2005; Collins and Walling, 2007; Collins *et al.,* 2010b). In the Cheaton Brook sub-catchment, the relative contributions from pasture surface sources ranged from 15% to 58% during this period, whereas contributions did not exceed 11% throughout the remaining sampling periods. Similarly, the corresponding relative contributions from areas of pasture in the Ridgemoor Brook sub-catchment ranged between 45% and 76%. Equivalent sediment contributions during the summer months (June – August) were as little as 7-8%, which coincided with a period of significant contributions from channel bank sources (Table 8.3). Although these greater channel bank contributions have already been attributed to higher rainfall intensity, Haley (2010) identified a possible “tipping point” in stocking density, when pasture contributions decrease relative to channel bank contributions. This therefore suggests that that when the pressure associated with pasture sources reached a certain point, significant sediment sources shifted from pasture to channel banks (Haley, 2010). This pattern is less pronounced in the Cheaton Brook sub-catchment, although the most significant channel bank contributions do coincide with periods of relatively low pasture contributions.

In contrast, significant pasture contributions were generally more consistent throughout the whole sampling period in the Curl Brook sub-catchment and as a result, ‘seasonal’ variations were more ambiguous. Although the largest pasture contribution was evident during an individual storm event in the autumn period, contributions from other storm events during this period were relatively low, ranging between 9% and 11% (Figure 8.29c). Seasonal patterns in relative sediment contributions from pasture surface soils were also less pronounced in the Moor Brook sub-catchment. For example, the most and least significant contributions were associated with storm events in the autumn period, where contributions ranged from a low of 2% (October – November) to a peak of 31% (September). When considering the magnitude and intensity of precipitation throughout individual sampling periods, it is evident that significant pasture contributions in this sub-catchment do not relate to periods of high intensity rainfall (Figure 8.29d). Nevertheless, when reflecting upon the autumn sampling period (sampling periods 7-9) it is apparent that the small pasture contributions in the latter part of this period (October – November) coincide with the least significant rainfall intensity. The insignificant contributions during the latter part of the autumn period could also reflect smaller stocking densities owing to specific in-wintering practices, where livestock, especially cattle, is ‘housed’ through the winter. As dairy farming is common in the Moor Brook sub-catchment (Natural England, pers. comm.), it is likely that grazing fields, which are easily poached, are left to rest over the winter period to encourage high quality grazing conditions in the following spring. Therefore, contributions from pasture source sources are significantly reduced during this period.

8.3.4 Woodland

The apportionment results show that significant woodland surface contributions in the Curl Brook sub-catchment were isolated to one individual storm event during the late autumn period (October – November). This could reflect the exposure of such surface soils to erosion and surface runoff following the inevitable seasonal reduction in vegetation density and canopy cover. However, seasonal variations in relative contributions from woodland sources are less pronounced in the Cheaton Brook sub-catchment, as contributions were generally more consistent throughout the whole sampling period. This suggests that sediment mobilisation and delivery from this source category is not entirely influenced by seasonal disturbances (Collins *et al*., 1997c), especially within a sub-catchment where bare soils are regularly associated with less developed woodland areas. When considering the rainfall intensity during individual sampling periods, it is apparent that the commencement of significant woodland contributions coincided with the greatest rainfall intensity (Figure 8.29a). For example, significant woodland contributions, ranging from 7% to 49%, only occurred during, and after, the high intensity storm events in June and July. Conversely, the preceding contributions were zero or so low that they were not recognised by the mixing model. This ‘pattern’ could conceivably reflect the distal locations of woodland sources relative to the catchment outlet (Owens *et* *al.,* 2000) and the considerable size of this particular sub-catchment (see Figure 3.17a). The associated sediment transit times are therefore likely to be substantial for this source type. As a result, the greatest woodland contribution of 49% occurred in the sampling period (July – August), which immediately followed the most intense rainfall event.

8.3.5 Farm Tracks

Significant contributions from farm track surfaces were extremely consistent throughout the whole sampling period in all four sub-catchments and as a result, considerable 'seasonal' variations were generally less pronounced. Nevertheless, it is evident that the most significant contributions occurred between May and June for the majority of the sub-catchments. These contributions, which ranged between 82% and 92%, coincided with silage production and field spraying activities within the catchment, when farm track surfaces are easily damaged and degraded through the frequent use of heavy farm machinery. Furthermore, it is apparent that the least significant individual contributions occurred during the autumn period (September – November). However, the timing of these relatively low contributions may reflect the more substantial contributions from other surface sources, rather than reduced rates of sediment delivery and mobilisation from this particular source. For instance, the least significant farm track contributions in the Cheaton Brook (14%) and Curl Brook sub-catchments (23%) were predicted for two individual sampling periods in the autumn, when equivalent contributions from pasture surface soils were most significant (58% and 50% respectively). In the case of the Ridgemoor Brook sub-catchment, sediment contributions from farm track surfaces were generally insignificant throughout individual sampling periods in the autumn and spring months (October – March), ranging from 2% to 5%. The corresponding contributions from arable and pasture surface sources (53% - 76%) were greatest during these periods (Figure 8.29b) suggesting that particular land use activities, such as harvesting, and variations in land cover have a superior influence on sediment contributions.

Owing to low infiltration rates (Ziegler *et al.,* 1997; Collins *et al.,* 2012a), farm tracks are particularly susceptible to extensive surface runoff during heavy rainfall events (Figure 8.32). Subsequently, it is not surprising that the most significant sediment contribution from farm track surfaces occurred in the sampling period immediately following the most intense rainfall event within the Ridgemoor Brook sub-catchment (Figure 8.29b). Further, it was apparent that the most insignificant sediment contribution from farm track surfaces coincided with the lowest intensity rainfall in the Cheaton Brook sub-catchment (Figure 8.29a). Therefore, it is likely that the differences in farm track contributions could be a result of inter-storm variations in the magnitude and intensity of precipitation rather than any distinct 'seasonal' patterns.

Figure 8.32 Surface runoff from a farm track directly connected to the channel network during a heavy rainfall event in the Lugg catchment (19th July 2012).

8.3.6 Summary

The sediment fingerprinting results have presented differences in the significance of various sources during different flood events throughout the sampling period. The observed temporal variations in relative source type contributions were generally a result of significant inter-storm variations in the magnitude and intensity of rainfall, along with variations in land use activities and land cover. However, these inter-storm contrasts can be obscured by seasonal trends making it necessary to assess such variability (Collins *et al*., 1997c). Although seasonal differences in the apportionment results have been inferred, it is important to recognise the temporal caveats associated with this variability. For instance, the elucidation of comprehensive seasonal trends was difficult owing to the relatively short overall sampling period (March –

November) and the subsequent omission of individual events throughout the winter months. Nevertheless, attempts have been made to consider seasonal patterns in the sediment contributions in relation to particular land uses in the four sub-catchments.

8.4 Summary

This chapter has presented the sub-catchment scale source apportionment results and the subsequent identification of the most dominant source types in four sub-catchments within the Lugg catchment. The sediment fingerprinting technique, using geochemical tracing properties, and supported through rigorous field reconnaissance, has identified that farm track surfaces are a significant source of suspended sediment in the Cheaton, Curl and Moor Brook sub-catchments. The dominance of farm tracks as a sediment source reflects the direct connectivity to the channel network, where mobilised sediment generated from by frequent use of heavy farm machinery and livestock trampling is efficiently delivered to the channel system. In contrast, arable surface soils are the most dominant source of fine sediment in the Ridgemoor Brook sub-catchment, whereas contributions from this source type are insignificant in the other three sub-catchments. Surface soils from pasture and channel bank material also represented important sources of fine sediment in the four sub-catchments. It is evident that the significance of the latter source is intimately linked to the importance of pasture sources, where channel bank degradation is often caused by severe livestock trampling. Finally, woodland surface soils are an important source of fine sediment in the Cheaton Brook sub-catchment. This source type represents the second most significant source of sediment in the Cheaton Brook, whereas the corresponding contributions in the Curl Brook sub-catchment are insignificant.

The dominance and variations in relative contributions from specific source types reflects a combination of factors controlling sediment mobilisation and delivery. These factors include variations in spatial coverage; land use activities and land cover; inter-storm variations in the magnitude and intensity of precipitation and the discharge response; connectivity between sources and the river network; catchment characteristics; slope and elevation of high risk fields;

and the particle size and clay content of channel banks. The relative merit of these factors has been considered and put into context with field reconnaissance and frequent discussions with the Stakeholder Advisory Group.

This sub-catchment analysis has identified the most significant sources of sediment in four of the sub-catchments previously identified as at risk of severe sediment runoff. The sediment fingerprinting procedure has provided a valuable tool for identifying and analysing the sources of fine sediment at the sub-catchment level, particularly when supported by rigorous field reconnaissance. It has therefore provided an evidence base to aid catchment management, identifying priority sources for which mitigation measures should be targeted to tackle fine sediment runoff in each sub-catchment.

CHAPTER 9
CONCLUSIONS

9.1 Summary of Findings

This research programme has investigated the sources and patterns of fine sediment movement in the Herefordshire Lugg catchment using an extensive spatial and temporal monitoring and modelling approach. Long temporal studies that monitor fine sediment delivery and provenance at the catchment scale are limited with reliable information on suspended sediment fluxes frequently short-lived or lacking. This information is non-existent in the Lugg catchment. Catchment managers therefore rely on annual average suspended sediment concentration data collected from 12 spot samples per annum at selected sites. This detailed study in an agricultural catchment in the UK capturing a series of fine sediment mobilisation events and modelling sources therefore provided the basis for developing 'weight of evidence' on the fine sediment problem in the catchment. Results from the individual components of the research programme have been discussed in detail in the latter sections of Chapters 5, 7 and 8. Results are synthesised here in terms of the overall aims of this study.

9.1.1 Spatio-Temporal Variations in Suspended Sediment

The first objective was to assess the spatio-temporal variations in suspended sediment delivered to key sites within the Lugg catchment. An assessment of the substrate quality and suspended sediment characteristics at each site using a freeze coring technique and deployment of time-integrated sediment samplers established considerable spatial variations in fine sediment at the monitoring sites. The lower parts of the Arrow (Broadward) and Lugg (Lugwardine) have greater proportions of fine sediment in the substrate material, greatly exceeding the 15 ± 5% < 2 mm threshold identified by early studies. This suggests that these sites have unfavourable salmonid spawning conditions. Furthermore, the average grain-size characteristics of suspended sediment collected at these sites are progressively finer relative to the corresponding values at the other three sites, with more than 98% of the material < 63 µm.

Suspended sediment concentrations vary at each site with high episodic values > 2,000 mg L^{-1} evident. All sites regularly exceeded the recently repealed annual average suspended solids guideline standard of 25 mg L^{-1} under the EC Freshwater Fish Directive. The greatest average concentrations over the entire period of study were found in the lower Lugg sites (Marlbrook and Lugwardine). However, the maximum concentration (>10,000 mg L^{-1}) was recorded at the Eaton monitoring site in the upper Lugg, although these values were sporadic and only represented 0.6% of the entire monitoring period. The absence of equivalently high concentrations at the two sites in the lower parts of the catchment reflect sediment dilution during higher flows associated with the more incised channel morphology. Although these concentrations are higher than what has been reported in other UK catchments (Walling and Webb, 1981), they are consistent with another study in the Lugg catchment, which investigated concentrations measured by the Environment Agency between 1992 and 2003 (D’Aucourt, 2004).

Considerable spatial variations in average specific suspended sediment yields were also reported at the monitoring sites. The greatest yields were associated with the lower parts of the Arrow and Lugg, although sites on the Lugg catchment displayed less variation than the Arrow sites. This suggests that mobilisation and transport of fine sediment in the River Arrow and Lugg get progressively higher as larger sub-catchments join the main channel. The River Arrow also has a detrimental effect on the sediment loads of the River Lugg, where total loads downstream of this confluence at Marlbrook are dramatically increased relative to the corresponding loads upstream at Eaton.

Temporal variations in suspended sediment were related to complex storm-specific interactions between discharge and sediment concentrations. These hysteresis relationships reflected variations in sediment supply and dominant source areas. Events over the study displayed clockwise, anti-clockwise and a complex interaction of both indicating that a mixture of within-channel and surface sources dominate during different flow events. The seasonal distribution of suspended sediment concentrations shows that the winter season poses the biggest threat of high values, with higher average concentrations recorded during this period at all sites, with the exception of Lugwardine.

This long-term monitoring record at key sites within the Lugg catchment has therefore established that high sediment loadings are a frequent occurrence. Calculated specific sediment yields exceed the typical values for UK rivers identified by Walling and Webb (1987). However, they are on the upper bound of suspended sediment yields recorded across England and Wales in agricultural catchments of a similar size.

9.1.2 Catchment Scale Sources of Fine Sediment

The second objective of this study was to determine the spatial provenance of fine sediment by utilising a sediment fingerprinting and mixture modelling approach. This catchment scale study identified tributary sub-catchments that persistently delivered fine sediment to key sites within the Lugg catchment over different temporal scales (Chapter 6). The sediment fingerprinting technique using geochemical tracing properties has identified the Cheaton, Ridgemoor, Curl, Stretford, Honeylake and Moor Brooks plus the Little Lugg as the predominant spatial sources of suspended sediment collected at the monitoring sites. These sub-catchments have been identified as at risk from diffuse pressures in the Lugg catchment through other studies, for example, the Rural Sediment Tracing Project (APEM, 2010) and wet weather sediment mobilisation and delivery studies (Environment Agency, 2006; McEwen *et al.,* 2011). Walling *et al.* (2008) also investigated sediment sources in the Streford Brook, which was identified for the targeted water quality monitoring programme implemented by the PSYCHIC study in the Herefordshire Wye catchment owing to its high-risk intensive arable agriculture. In addition, sub-catchments located in the upper parts of the catchment have been identified as dominant sources of fine sediment. These include the un-named tributaries at Treburvaugh and Lucton and the Glasnant sub-catchment.

The observed spatial and temporal variations in relative source type contributions estimated by the mixing model reflect a number of factors that control variations in sediment mobilisation and delivery from individual source types. These factors include variations in catchment area and the spatial distribution of source areas; elevation and slope across the study catchment; the underlying soil type of individual source areas; land use activities and land cover; inter-storm variations in the magnitude and intensity of precipitation; proximity of source areas to sampling points; and localised catchment events (Collins *et al.,* 1997c, Walling *et al*., 1999b, Collins *et al*., 2001; 2010b; Owens *et al*., 2016). The relative merit of these factors has been considered and put into context with field reconnaissance and frequent discussions with the Stakeholder Advisory Group.

The dominance and variations in relative source type contributions from specific tributary sub-catchments is likely to reflect a combination of all factors controlling sediment mobilisation and delivery. For instance, although the apportionment results demonstrate that the significance of relative source contributions generally do not mirror the associated catchment area of each tributary sub-catchment, the two sub-catchments with the greatest load-weighted fine sediment contributions at the Eaton monitoring site were estimated to be derived from tributary sub-catchments with the largest catchment areas. However, it is evident that this relationship is not displayed in other contributing sub-catchments at this monitoring site, suggesting that additional factors are at play in controlling sediment loss from individual sub-catchment sources. These additional factors could include differences in the topography (slope and elevation) across the study catchment (Lintern *et al*., 2018). The source apportionment results demonstrate that the majority of sub-catchments that persistently deliver fine sediment to the monitoring sites are characterised by low elevation. It is evident that lowland erosion was a more important source of sediment than the upland areas. Nevertheless, two of the most persistent contributors of fine sediment are located in the upper parts of the catchment with high elevation. Therefore, variations in sediment contributions could be controlled by land use and the prevailing soil type regardless of slope (Ayele *et al.,* 2017).

The relative importance of catchment sources and associated spatial variations in sediment provenance can also be determined by the soil type and underlying geological characteristics of source areas (Miller *et al*., 2013). The source apportionment results demonstrate that the majority of sub-catchments that persistently deliver fine sediment to the monitoring sites are characterised by soil easily susceptible to erosion during heavy rainfall events. However, this does not fully reflect the variations in sediment contributions as two individual sub-catchments that persistently deliver fine sediment are characterised by different soil types, less susceptible to water erosion.

In addition, variations in land cover, the timing of associated activities and the connectivity between high risk fields and the river channel network within individual tributary sub-catchments were also shown to have an influence on the spatial and temporal variations associated with fine sediment contributions (Collins *et al*., 2010b). For instance, the greatest sediment contributions at the Eaton monitoring site were associated with sub-catchments with large arable land coverage. The relatively high contributions from the un-named tributary at Lucton, evident during the winter season, could be attributed to the location of large arable fields adjacent to the watercourse which were characterised by small channel margins with evidence of major sediment runoff and deposition. Furthermore, the type of crop cover can have an influence on the variations in sediment contributions, which was identified in the Honeylake Brook sub-catchment owing to the large areas of soft fruit production under polytunnels. Significant contributions from this source area were associated with the period immediately before and succeeding this land use activity associated with a high erosion risk and subsequent fine sediment delivery to the channel network (Walling *et al*., 1999a; Walling 2005; Collins and Walling 2007a; Collins *et al*., 2010b).

The complex temporal variations in sediment sources also reflected differences in the magnitude and intensity of precipitation and its spatial distribution. For example, the greatest contributions of fine sediment from tributary sub-catchments located in the upper parts of the Lugg and characterised by steeply incised actively eroding channel banks occurred during the 2012 summer season which was associated with the highest intensity rainfall over the whole monitoring period. The responsive nature of the channel network, aslong with the steep sided channel banks, is likely to significantly increase the detachment and entrainment of channel bank material during these high-energy events (Walling *et al.,* 1999b; Owens *et al.,* 2000; Collins 2008). Therefore, the dominance of the un-named tributary at Treburvaugh in particular, is likely to reflect the occurrence of several extreme rainfall events and subsequent channel bank erosion. Furthermore, the occurrence of the Glasnant sub-catchment as a main contributor of fine sediment before ceasing between January and March 2011 reflects an extreme rainfall event confined to the upper parts of the catchment in October 2010, followed by major bank collapses. Fine sediment was flushed out through the system during this first major flood event of the season, which coincided with the time when particle availability is at a maximum following a dry summer (Lefrançois *et al.,* 2007). This exhausted the sediment supply in the months preceding the event (Steegen *et al*., 2000; Hudson, 2003; Oeurng *et al*., 2010).

In addition to variations in the magnitude and intensity of precipitation, the proximity of tributary sub-catchments relative to individual sink sites is a potential control determining the relative importance of catchment sediment source areas. The mixing model outputs indicated that some dominant sub-catchments situated close to the monitoring sites contribute high proportions of fine sediment. Sediment mobilised from these sub-catchments is only entrained in the river channel network for a relatively short amount of time and is therefore less likely to be subjected to conveyance losses such as those associated with overbank deposition (Walling *et al.,* 1999b). For example, the Honeylake Brook sub-catchment is situated directly upstream of the Broadward monitoring site and is associated with the greatest sediment contributions. Contributions from this sub-catchment predominate during low energy low events when sediment mobilised from other tributary sub-catchments further upstream is unable to be transported through the channel network. Nevertheless, despite the close proximity of other sub-catchments to a specific monitoring site, contributions were equally as high at other sites further downstream.

Temporal variations in fine sediment contributions were associated with localised catchment events which could determine the relative importance of sediment source areas during different sampling periods that were not necessarily related to rainfall variations. This was most notable in the Wellington Brook sub-catchment, where a program of in-channel works involving the installation of check weirs backfilled with alluvial gravel to increase flows and provide suitable spawning sites directly coincided with a shift in dominant source areas contributing to the suspended sediment load at the Lugwardine monitoring site.

Therefore, this catchment scale sediment provenance analysis has identified sub-catchments that persistently contribute sediment to key monitoring site in the Lugg catchment and has assisted in strengthening evidence of the sediment problem in the Lugg catchment. It has put relative sediment contributions in context with the factors that control sediment mobilisation and delivery to understand the spatial and temporal variations evident across the catchment. Furthermore, it has provided an evidence base to aid catchment management by identifying priority areas for which mitigation measures should be targeted to tackle the fine sediment problem.

9.1.3 Sub-Catchment Sources of Sediment Delivery

The third objective was to identify and evaluate sub-catchment sources of fine sediment based on different land use types by using a developed sediment sourcing methodology (see Chapter 5). The catchment scale sediment sourcing results identified a number of tributary sub-catchments that persistently delivered fine sediment to key sites in the Lugg catchment. Building on this, and through discussions with the Stakeholder Advisory Group four sub-catchments (Cheaton Brook; Ridgemoor Brook; Curl Brook; Moor Brook) were identified for the purpose of this sub-catchment scale study. The sediment fingerprinting technique using geochemical tracing properties and supported through rigorous field reconnaissance has identified that farm track surfaces are the most significant source of fine sediment in the Cheaton, Ridgemoor and Curl Brook sub-catchments. This supports the findings of other fingerprinting studies undertaken in agricultural catchments in the UK (e.g. Collins *et al*., 2010c; 2012a). In contrast, arable surface soils are the most dominant source of fine sediment in the Ridgemoor Brook sub-catchment, whereas contributions from this source type are insignificant in the other three sub-catchments. Surface soils from pasture and channel bank material also represented important sources of fine sediment in the four sub-catchments. Finally, woodland surface soils are an important source of fine sediment in the Cheaton Brook sub-catchment, representing the second most significant source, whereas the corresponding contributions in the Curl Brook sub-catchment are insignificant.

The dominance and variations in relative contributions from specific source types reflects a combination of factors controlling sediment mobilisation and delivery. The controls on sediment mobilisation influencing the relative importance of source types are shown in Table 9.1. These factors include variations in spatial coverage; land use activities and land cover; inter-storm variations in the magnitude and intensity of precipitation and the discharge response; connectivity between sources and the river network; catchment characteristics; slope and elevation of high risk fields; and the particle size and clay content of channel banks. The relative merit of these factors has been considered and put into context with field reconnaissance and frequent discussions with the Stakeholder Advisory Group.

Table 9.1 The factors that control sediment mobilisation and delivery from the different source types examined in the Lugg catchment.

Control	**Source type**				
	Farm Tracks	**Arable**	**Pasture**	**Woodland**	**Channel Banks**
Spatial coverage	✗	✗	✗	✗	✗
Location and connectivity with channel network	✓	✓	✓	✓	
Topographic characteristics (slope / elevation)	✓	✓			✓
Land use pressure					✓
Land management activities	✓	✓	✓		
Magnitude and intensity of precipitation	✓	✓		✓	✓
Vegetation cover				✓	✓
Particle size (clay content)					✓
Channel response to rainfall					✓

The dominance of farm tracks as a sediment source reflects the direct connectivity to the channel network, where mobilised sediment generated from by frequent use of heavy farm machinery and livestock trampling is efficiently delivered to the channel system (Collins *et al.,* 2010c). There is a large spatial variation in the relative importance of this source type owing to the characteristics of the individual sub-catchments and the proximity of these features to the channel network. For example, farm tracks are commonly located in close proximity to the channel network in the Cheaton, Curl and Moor Brook sub-catchments. Consequently, they are directly connected to the river channel system, with steep slopes encouraging significant erosion during heavy rainfall events and the delivery of loose erodible material. In contrast, farm tracks in the Ridgemoor Brook sub-catchment demonstrated lower connectivity as they are generally located adjacent to the channel network. As a result, the delivery of fine sediment mobilised from the farm tracks in this sub-catchment is significantly reduced. The topographic characteristics (slope and elevation) of the sub-catchments could also control sediment mobilisation and delivery from farm track sources. For example, the Cheaton and Curl Brook sub-catchments with significant contributions from farm track surfaces are characterised by high elevation. However, this is not the case in the Moor Brook. Land management activities have also been shown to control sediment mobilisation and delivery from farm track sources (Table 9.1). Farm tracks in the Ridgemoor Brook were less frequently used owing to the limited surface damage and degradation compared with the other three sub-catchments. When considering the inter-storm variations in the significance of farm track surfaces, it is evident that land use activities during particular times of the year and, to a lesser extent, rainfall intensity have a significant impact on sediment contributions from this source type. For example, the most significant contributions from these surface sources coincided with the main land management activities involving silage production and field spraying, when increased farm traffic occurs.

The load-weighted mean sediment contributions from arable surface soils are generally insignificant in most of the sub-catchments despite their relatively large areal extent, indicating that spatial coverage does not control sediment mobilisation and delivery from this source type. However, arable sources were identified as the most important source of sediment in the Ridgemoor Brook sub-catchment. This distinct spatial variation reflects apparent differences in the sub-catchment characteristics. For example, arable fields in this sub-catchment were located in the lower part of the catchment and were therefore not subjected to losses such as overbank deposition before reaching the catchment outlet (Walling *et al.,* 1999b). In contrast, most of the intensive arable farming, in particular potato cultivation, was confined to fields located in the upper parts of the Cheaton Brook catchment, which is associated with low contributions from this source type. The relative importance of arable surface soils also reflected the size of channel margins and occurrence of buffer strips in the sub-catchments. In the Ridgemoor Brook sub-catchment, smaller channel margins were evident, whereas larger channel margins and buffer strips were evident in the other sub-catchments. Furthermore, the connectivity of arable fields with the river network in the sub-catchments could control sediment mobilisation and delivery from this source type. Important inter-storm variations in the significance of arable surface soils reflect seasonal patterns in land use activities and variations in land cover. The most significant contributions from arable surface sources were immediately following harvest activities, which followed a period of bare ground. These temporal variations also relate to patterns in rainfall intensity, when sediment mobilisation is particularly high during heavy rainfall events.

In general, pasture surface soils represented an important source of fine sediment in most of the sub-catchments. However, despite the particularly large spatial extent of pasture fields in one sub-catchment, the associated mean relative sediment contribution appears to be relatively insignificant. This suggests that spatial coverage does not control sediment mobilisation and delivery from this source type (Collins *et al*., 2010b). The distinct spatial variation might therefore reflect differences in the sub-catchment characteristics. Field reconnaissance suggests that pollution from this source type is influenced by the severity of surface soil poaching associated with livestock type and stocking densities, along with the connectivity between pasture fields and the channel network. For example, cattle grazing was particularly common in the Ridgemoor, Curl and Moor Brook sub-catchments leading to intensive poaching around channel margins, gateways and feeding rings. Surface degradation and poaching associated with sheep grazing in the Cheaton Brook sub-catchment was not as intensive, reflecting the lower contribution from the pasture source category in this sub-catchment. Inter-storm variations in the significance of pasture surface soils mainly reflect localised disturbances to the channel margin, where contributions are evidently greater during the autumn period when such surfaces are frequently characterised by high soil moisture content and waterlogging.

Channel bank material also represented a significant source of suspended sediment in each of the four sub-catchments. It is apparent that the significance of channel bank sources is intimately linked to the importance of pasture sources, where aggravated channel bank erosion is often caused by severe livestock poaching. Bank trampling and degradation of the channel margins was particularly evident in the Ridgemoor Brook sub-catchment, which was associated with the greatest channel bank contributions. Nevertheless, the spatial variation in sediment contributions between different sub-catchments is relatively insignificant. Variations in sediment mobilisation and delivery from channel banks sources in individual sub-catchments could also be controlled by the particle size and the average silt-clay content of the actively eroded material (Couper, 2003). The sub-catchment with the least significant contributions from channel bank sources is associated with the highest silt-clay content. However, this relationship is not observed in the Ridgemoor Brook sub-catchment, indicating that additional factors could control variations in the relative importance of channel bank sources. When considering the inter-storm variations in the significance of channel bank sources, it is evident that rainfall intensity has a significant impact on sediment contributions from this source type. The greater erosive capacity of the channel during intense flood events dramatically increases the detachment and entrainment of channel bank material and as a result, sediment contributions are considerably increased during these periods.

It is evident that there are significant spatial variations in woodland surface soil sediment contributions. Although the spatial extent of this particular source type is low, woodland topsoils represented the second most significant source of fine sediment in one sub-catchment, whereas contributions were insignificant in the other sub-catchment. These distinct spatial variations reflect the different characteristics of woodland areas in each sub-catchment, where enhanced sediment contributions are associated with immature plantations adjacent to the river network. Considerable inter-storm variation in the significance of woodland surface soils reflect differences in rainfall intensity in these areas, where bare soils are more exposed to erosion and surface runoff. However, a pronounced seasonal pattern is evident in more developed woodland areas, when greater sediment contributions reflect the exposure of surface soils during the reduction in vegetation density and canopy cover throughout the autumn period.

This sub-catchment scale sediment provenance analysis has therefore identified the most significant sources of sediment in four of the sub-catchments previously identified as at risk of severe sediment runoff. It has put relative sediment contributions in context with the factors that control sediment mobilisation and delivery (Table 9.1) to understand the spatial and temporal variations evident across the sub-catchments. Furthermore, it has provided an evidence base to aid catchment management by identifying priority sources for which mitigation measures should be targeted to tackle the fine sediment runoff in each sub-catchment.

9.2 Implications for Management

Sustainable catchment management requires an appropriate scientific underpinning that establishes the temporal chapter of fine in-channel sediment and its sources within the wider catchment. Source type contributions significantly vary between catchments. It is therefore understood that catchment-specific fingerprinting approaches are most valuable for catchment managers to target sediment control. This research has utilised a coupled field monitoring and modelling approach to identify catchment-specific sources. Through this, a number of sub-catchments that persistently deliver fine sediment to key sites in the Lugg catchment have been identified. Fine sediment management should therefore target these priority areas to enable mitigation resources to be successfully targeted. Furthermore, specific source types at the sub-catchment level have been investigated to help further target appropriate mitigation measures to tackle the high sediment loadings.

Figure 9.1 illustrates a conceptual model classifying the sources of suspended sediment identified in the Lugg catchment. Through the catchment scale analysis (see Chapter 6) four tributary sub-catchments that persistently delivered fine sediment to key sites were identified. Therefore, these should act as priority areas for which mitigation measures should be targeted to help tackle the siltation problem in the Lugg. Ranked in order of importance according to the load weighted mean sediment contributions, it is evident that mitigation measures should firstly be targeted in the Cheaton Brook sub-catchment, which is the most dominant source of fine material in the catchment-scale provenance study. The load weighted mean contributions from this source area ranged between 10 and 23% at the monitoring sites, with maximum contributions of 64% (Appendix 2.3). Mitigation measures should also be targeted in the Curl and Ridgemoor Brook sub-catchments, which persistently contributed to the fine sediment loadings in the wider catchment. Respective load weighted mean contributions ranged between 8 and 15% and 5 and 16%. Although, the sediment contributions from the Moor Brook sub-catchment are less important in comparison with the other three, it was evident from the catchment scale provenance study that this sub-catchment persistently delivered sediment to the sink sites. Therefore, mitigation strategies employed in this sub-catchment will help tackle the fine sediment problem in the Lugg.

However, the sub-catchment scale provenance study (see Chapter 8) has shown that source types differentiate between sub-catchments. As a result, sediment management strategies will need to be tailored according to the prominent source types in each sub-catchment. Figure 9.1 illustrates the relative importance of different source types in each of the four sub-catchments. Surface soils represent the most significant source of fine sediment in each priority area, accounting for approximately 80% of the sediment load. This is similar to other studies that have investigated surface and channel bank sources and reported surface contributions ranging between 74 and 96% (Walling, 2005; Walling *et al.,* 2008; Collins *et al*., 2010b; 2012b). This suggests that mitigation measures designed to tackle fine sediment runoff should incorporate strategies to control surface erosion. More specifically, the sediment fingerprinting results in this study indicate that if siltation problems in the Lugg catchment are to be tackled effectively, catchment managers should target the reduction of fine sediment from farm track surfaces in the Cheaton, Curl and Moor Brook sub-catchments, while targeting the reduction of sediment mobilised from arable and pasture surfaces in the Ridgemoor Brook sub-catchment.

Potential mitigation measures that could be implemented in the Lugg catchment are detailed in Table 9.2. The measures are ranked in order in terms of source type and sub-catchment. For example, measures concerning farm track management should be prioritised given the significance of these sources (Figure 9.1). Farm tracks increasingly act as concentrated flow pathways for diffuse pollutants including sediment. The high connectivity of tracks within the Lugg catchment and the high proportion of sediment generated from this source type suggest that management should focus on farm track remediation work (e.g. Collins *et al*., 2010c). Potential mitigation measures that could be deployed range from measures that tackle the source of sediment runoff e.g. resurfacing with compacted stone, to measures that help alleviate the problem e.g. runoff diverters and collectors installed to intercept runoff. In addition, the relative importance of arable surface soils in the Ridgemoor Brook suggests that measures targeting the reduction of sediment mobilised from arable surfaces should be prioritised in this sub-catchment. Potential mitigation measures are associated with ‘trapping’ runoff and sediment before entering the watercourse (Table 9.2). It is recommended that establishing riparian buffer strips in the Ridgemoor Brook would be advantageous owing to the occurrences of these in the other three sub-catchments and the associated low contributions from this source type. An assessment of mitigation methods by Anthony and Collins (2006) reported that the effectiveness of riparian buffer strips in reducing diffuse pollutant losses ranges between 5 and 30% with the upper value associated with sandy soils. When considering the nature of the soils in the Lugg catchment (see Chapter 2), it is evident that this mitigation measure will be effective.

To tackle the issues of fine sediment in the catchment, catchment managers should also target the reduction of fine sediment from grazed surface soils, particularly in the Ridgemoor and Curl Brook sub-catchments (Figure 9.1). Furthermore, although channel bank erosion represents a less important source of fine sediment compared to surface soils, the relative contributions in each sub-catchment suggests that measures targeting the reduction of channel bank erosion should also be undertaken. A potential mitigation measure of fencing off streams and rivers from livestock will help stabilise channel banks and reduce aggravated bank erosion. The importance of land management activities in relation to aggravated bank erosion through livestock poaching has been discussed in Chapter 8 (section 8.2.4). By fencing off streams and limiting poaching and direct runoff from grazed surface soils, contributions from channel banks sources should be reduced. It is therefore recommended that this measure is prioritised in the Ridgemoor and Curl Brook sub-catchments, where temporal variations in sediment sources show that pasture and channel bank sources are connected through a “tipping point” in stocking density (see Chapter 8, section 8.3.3).

The relative importantance of different source areas and types identified in the Lugg catchment (Figure 9.1) therefore indicates that a range of sediment mitigation strategies need to be focused on which need to be tailored to individual sub-catchments, rather than using a ‘one-method fits all approach’.

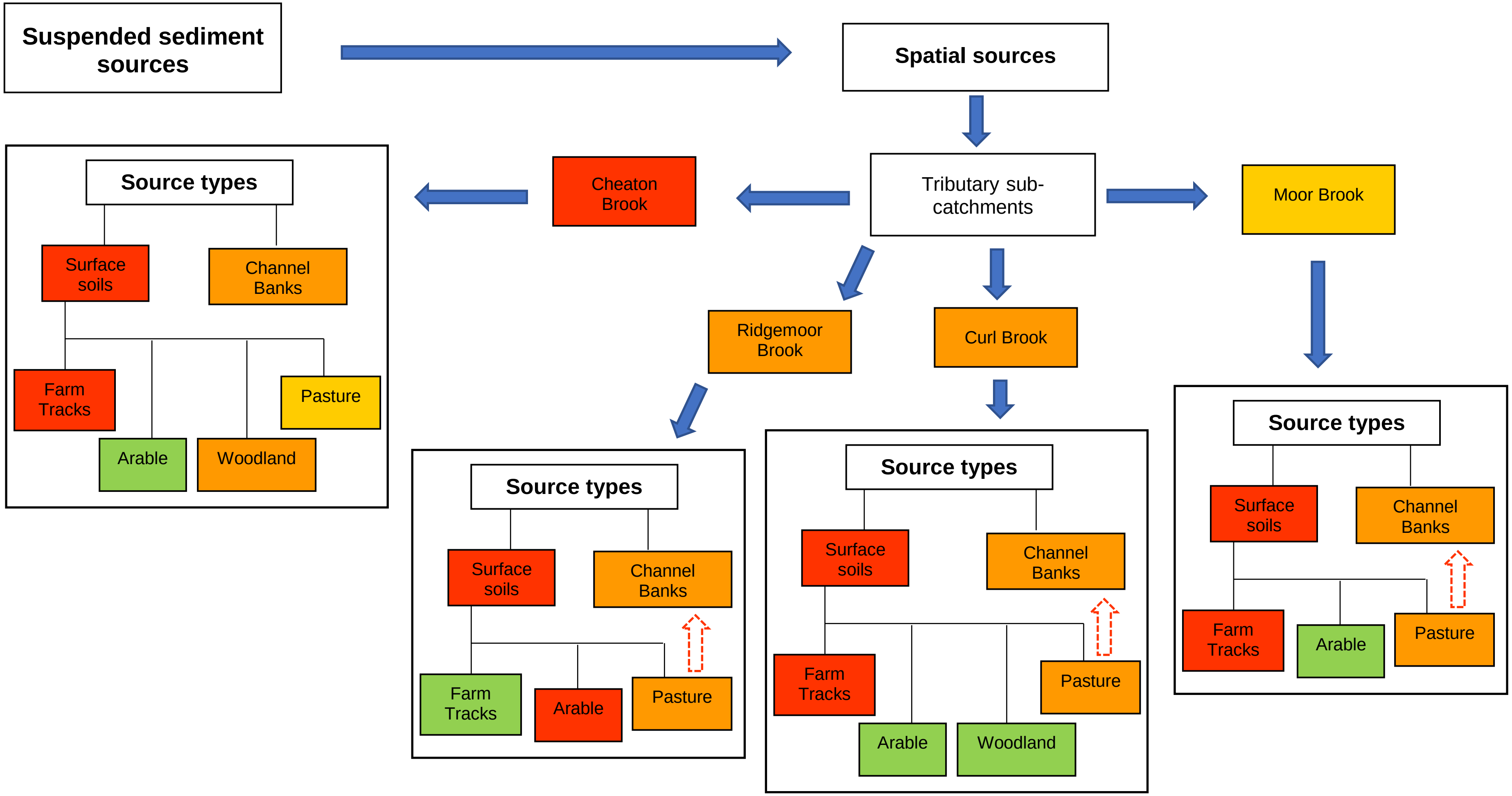

Figure 9.1 Conceptual model showing the fine sediment sources identified in the Lugg catchment through the sediment fingerprinting procedure with sources ranked from high (red) to low (green) significance.

Table 9.2 Potential mitigation methods that could be implemented in the Lugg catchment ranked in order of importance in terms of source type and sub-catchment.

Source Type	Sub-Catchments	Potential mitigation measures
Farm track surfaces	Moor Brook Curl Brook Cheaton Brook	Runoff diverters and collectors installed to intercept runoff and sediment. Resurfacing of badly eroded sections of track with compacted stone. Vehicle traffic reduced or avoided during wet weather periods. Raising the surface level of tracks to avoid rainwater and field runoff. Strategically placed grips to help reduce the risk of wheel rutting.
Arable surface soils	Ridgemoor Brook	Establish riparian buffer strips to trap mobilised sediment during runoff events. Sediment ponds and traps to provide area where sediment can settle following runoff. Filter fences and banks to intercept runoff and trap sediment.
Grazed surface soils	Ridgemoor Brook Curl Brook Moor Book	Fence off rivers and streams from livestock to stabilise river banks and reduce aggravated bank erosion. Provide in-field watering points to prevent livestock from needing to enter the river channel. Establish un-grazed buffer strips to trap mobilised sediment during runoff events. Reduce length of grazing season preventing livestock grazing during high risk times.
Channel banks	Ridgemoor Brook Curl Brook Cheaton Brook Moor Brook	Fence off rivers and streams from livestock to stabilise river banks and reduce aggravated bank erosion. Bank stabilisation and protection schemes.

Figure 9.1 shows a cascade of scales used in this sediment fingerprinting study which could be challenging when developing management plans for the whole catchment. Management plans are normally developed for whole river basins or

catchments, rather than for the sub-catchment scale. It was therefore necessary to provide an initial assessment on the source types for the whole Lugg catchment by scaling up the sub-catchment source provenance results. By combining the load weighted mean spatial source estimates from the catchment scale study (as presented in Chapter 6) with the source type contributions for the four sub-catchments (Chapter 8), a weighted mean sediment contribution from each source type to be calculated for the Lugg catchment outlet (e.g. Collins *et al*., 2009). Figure 9.2 shows the spatially weighted mean relative contribution for each sediment type for the River Lugg catchment. These estimates provide a more meaningful assessment of the typical source type to suspended sediment collected from the catchment outlet compared to simply averaging the mixing model output for the four sub-catchments. It is evident that farm track surfaces still represent the most dominant source type, although the importance of this source type has been diluted through scaling up. Channel banks sources represent the second most significant source type, suggesting that mitigation measures identified above should be prioritised after that of farm tracks surfaces. In contrast, arable surface soils are less important at the catchment scale compared to the sub-catchment scale (i.e. in Ridgemoor Brook). This suggests that although arable sources are dominant in particular sub-catchments, the impacts of these sources at the catchment scale are less significant. Therefore, mitigation measures identified in Table 9.2 are better placed at tackling sediment runoff from farm tracks and pasture surface soils, as well as channel bank degradation and aggravated bank erosion.

Sediment loads from individual areas and source types may be reduced by implementing the suggested mitigation measures. In order to help measure the effectiveness of such mitigation options, a further sediment provenance study will be required once the measures have been established. A similar study has been undertaken on the Dorset Frome, Exe and Axe CSF priority catchments, (Collins *et al.,* 2017), which enabled the effectiveness of such mitigation measures to be analysed in regard to future policy impacts. However, as the fingerprinting procedure is based on relative sediment contributions and therefore not reflecting total sediment load from the different source types, it is likely that any improvements in source contributions may be supressed. As a result, it is important an assessment on sediment loads is made to relate the relative proportions to the actual amount of sediment delivered to key sites. However, this catchment scale source type assessment is based on four sub-catchments, rather than all of the main contributors of sediment in the Lugg (identified in Chapter 6), and whilst this study has provided a scientific evidence base on the sources of fine sediment, further provenance studies are required to assess the wider implications.

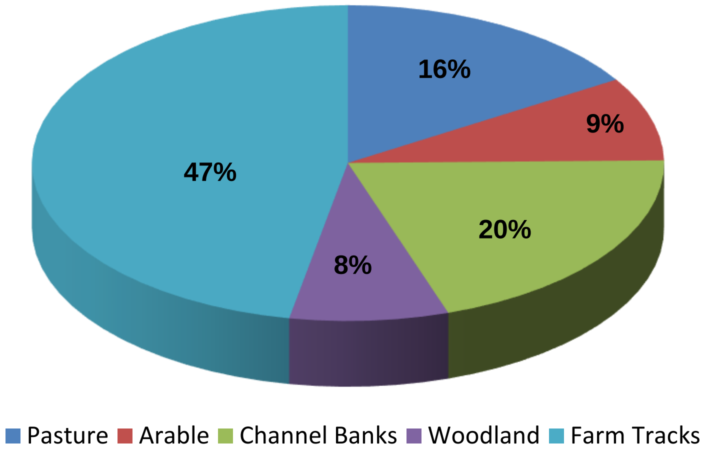

Figure 9.2 The spatially weighted mean relative contribution for each sediment type for the River Lugg catchment (Lugwardine monitoring site).

9.3 Limitations and Suggestions for Further Work

Table 9.3 details the uncertainties associated with the different methods utilised in this study. Each uncertainty will be discussed in light of limitations of the study and recommendations for further work.

Table 9.3 Uncertainties associated with the methods utilised in this study ranked in order of uncertainty.

Method	Uncertainties
Sediment fingerprinting	Misclassification of source material during the statistical procedure
	Exclusion of fingerprint properties from a wide range of different subsets
	Spatial variability of source material properties
Suspended sediment-turbidity rating curves	Probe failure and data drift associated with optical turbidity probes
	Capturing peak suspended sediment concentrations during flood events
Sediment sampling	Failure to incorporate all potential source types in the catchment
	High number of sub-catchments used as potential source areas
	Timing and frequency of the source sampling
	Number of flood events sampled
Stage-discharge rating curves	Failure to undertake velocity measurements over sufficient flow events
Temporal analysis	Based on seasons of winter (October-March) and summer (April-September) rather than timings of land use activities

9.3.1 Sediment Fingerprinting Uncertainties

An important uncertainty associated with the sediment fingerprinting technique is related to the misclassification of source material during the statistical procedure. If source samples are incorrectly classified during the discriminant function analysis, the prediction of sediment contributions from different source groups may be affected. In this study, the greatest misclassification of source materials was associated with farm track surfaces in the Moor Brook sub-catchment (see Chapter 7, section 7.3.2). Only 50% of these samples were correctly classified, with the others being incorrectly predicted as belonging to the arable source group. Therefore, it is possible that contributions from arable surface soils have been unrepresented in the mixing model algorithm for the Moor Brook sub-catchment. This could present an important limitation when identifying where to target mitigation measures in the catchment. This misclassification between farm track surfaces and surface topsoils is exaggerated by the fact that farm tracks surfaces can present both a primary and secondary source of sediment. For example, where farm tracks are located in or close to fields, the tracks can act as a runoff pathway delivering sediment originating from surface soils. Similarly, misclassification was also associated with arable surface soils in the Cheaton Brook sub-catchment, where 36% of the misclassified samples were incorrectly predicted as belonging to the pasture source group. This reflects the rotational land use in the Lugg catchment, were agricultural land activities are often rotated to improve soil health. As a result, geochemical signatures associated with the two source types could be mixed, highlighting the need to incorporate a number of different diagnostic properties from a wide range of different subsets.

The exclusion of fingerprint properties from a wide range of different subsets also represents a limitation in sediment fingerprinting studies. The composite fingerprints used to discriminate sources in this study were based solely on geochemical properties. The DFA results presented in Chapter 7 are slightly lower than figures presented in other studies (Table 7.27). The homogenous geology and soil type of the Lugg catchment are likely to be important factors limiting the discriminating power of the final composite signature. Therefore, further source apportionment in this catchment would have to incorporate a greater number of geochemical properties or a mixture of other types of properties, for example mineral-magnetic, radionuclide, geochemical and organic elements.

The spatial variability of source properties is also a potential uncertainty in the sediment fingerprinting approach. Although this variability was accounted for in the source sampling methodology by taking representative samples, studies have found a wide variability in fingerprint properties across field areas (Du and Walling, 2017). This represents a potential problem for the fingerprinting approach and therefore requires further exploration in future studies in order to identify the nature and magnitude of such variability and its wider implications for the approach.

9.3.2 Suspended Sediment-Turbidity Rating Curve Uncertainties

An important uncertainty associated with the suspended sediment-turbidity rating curve method is related to probe failure and data drift associated with optical turbidity curves. The turbidity sensors used in the study occasionally failed resulting in data loss. This was minimised by visiting field sites once a month, however, there were times when probes failed resulting in a loss of data for a period of time. Monitoring stations with advanced equipment enabling 'real-time' data to be accessed remotely would help to avoid these situations and therefore long-term monitoring suspended sediment monitoring projects in the future should use this equipment. However, the high cost of this equipment made this option unfeasible for this study. The turbidity sensors were also subject to lens obscuration due to debris collection and algae growth and subsequently resulted in data inaccuracy. Although this was reduced through regular cleaning, it is possible that suspended sediment concentrations and loads are over-estimated. Self-cleaning turbidity sensors are now widely available, which would prevent these issues. Therefore, future work should utilise these to reduce data inaccuracy.

Suspended sediment concentrations and loadings were calculated through the development of site-specific rating curves based on individual flood events. It is important to capture peak suspended sediment concentrations during flood events to gather suspended sediment data over the full hydrograph response and over different flow events. In addition, this research has demonstrated that the relationship between flow and suspended sediment is complex and site specific with hysteresis loops. Therefore, it is possible that the rating curve relationship during different seasonal events may differ. Harrington and Harrington (2012) generated different rating curves for individual sites based on seasonal events. Further suspended sediment work could therefore adopt this approach to reduce error.

9.3.3 Sediment Sampling Uncertainties

The failure to incorporate all potential source types within the catchment is an important uncertainty associated with source provenance studies. Although, the research design incorporated the main source types based on the prevailing land-use and previous studies in the available literature (see Chapter 3), it is apparent that other sources of fine sediment could contribute to the suspended sediment loads. For example, the importance of hopyards and field drains as sources of fine sediment have been demonstrated in previous studies (Russell *et al.,* 2001). Road surfaces have also been identified as representing an important source of fine sediment (Gruszowski *et al.,* 2003), along with organic sources such as farm yard manure and in-stream decaying vegetation (Collins *et al.,* 2013b; Zhang *et al.,* 2014). The discrimination offered by the final composite fingerprint during the provenance sourcing method could be reduced if potentially important sources of sediment are ignored. The effect of this was shown by Collins *et al*. (2013a) who found that discrimination was greatly enhanced in the Lugg catchment by incorporating a number of organic sources in the analysis. Therefore, it is recommended that future sediment fingerprinting studies in the Lugg and other agricultural catchments in the UK, should incorporate organic sources of sediment into the sampling design

Another important uncertainty associated with sediment source sampling involves the number of potential source categories used in the analysis. The catchment sourcing methodology utilised in the study incorporated a high number of potential sub-catchments, which may not satisfy dimensionality. Therefore, improved reliability is likely to be obtained with a reduced number of source areas, possibly by combining adjacent sub-catchment areas. As a result, future work could adopt a 3-phased approach, where potential source areas are firstly discriminated before individual sub-catchments within these are investigated before sub-catchment sources are investigated. Nevertheless, sub-catchments identified as persistent contributors of sediment in this study are consistent with sub-catchments identified at high risk of sediment erosion.

Furthermore, the representativeness of the sediment provenance data obtained in this study to determine catchment scale sediment sources may have been biased by the timing of the source sampling and the fact that a single sediment campaign was undertaken. Source sampling took place during the summer months when river levels permitted access to the potential sources in the catchment. However, the provenance of fine grained channel bed sediment can vary seasonally in response to the hydrological regime and the seasonal pattern of land use (Jones *et al*., 2016). Nevertheless, it has been argued that single visit downstream channel bed sediment sampling is reliable in characterising bed-sediment associated geochemistry (Horowitz *et al*., 2012).

An important uncertainty associated with sediment sampling is related to the number of flood events sampled. The sub-catchment sediment sourcing methodology was based on a relatively short timescale (March-November 2012). Ideally, this should have been based on a full year to identify any potential differences in sediment sources with flow events. For example, it would be expected that farm track surfaces would be a dominant source of sediment during low flow events due to their immediate connectivity with the channel. Therefore, it is possible that other sources would have been more dominant during the un-sampled winter months, impacting the load-weighted mean. However, the 2012 summer period was particularly wet, enabling a range of different flow events to be sampled.

9.3.4 Stage-Discharge Rating Curve Uncertainties

Failure to undertake velocity measurements over sufficient flow events could have an impact on the accuracy of the stage-discharge rating curves. When producing stage-discharge rating curves it is important to characterise a number of flow events including the extreme events to be able to confidently predict discharge. However, owing to the incised nature of the river channels in the lower parts of the catchment and the flashy river regime in the upper parts of the catchment, cross-sectional velocity measurements were not feasible during periods of extreme flow conditions. The ‘float method’ was therefore used during these periods which is associated with uncertainty. Nevertheless, three gauging stations were located close of monitoring sites in the catchment, and therefore discharge data from these were used to verify the accuracy of the stage-discharge rating curves.

9.3.5 Temporal Analysis Uncertainties

In addition to uncertainties associated with methods, a potential limitation was associated with the temporal scale analysis. The temporal analysis in this study was based on seasons of winter (October-March) and summer (April-September) rather than timings of land use activities. Although is a standard approach in the literature it does not relate to the schedule of land management and farming activities. In catchments that are dominated by agricultural land management practices it might be better to group temporal variations into the main farming activities and associated land cover identified in Table 6.4. For example, temporal variations could be based on the contrasts in sediment contributions throughout field preparation, crop growth, harvest and bare ground, rather than the standard seasonal contrasts. However, as land cover is constantly changing owing to specific crops requiring field rotations e.g. potatoes, for simplicity and to keep it in line with other sediment fingerprinting studies, the temporal analysis in this study was based on seasons of winter and summer.

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APPENDICES

APPENDIX 1:

Summary characteristics of suspended sediment collected at the monitoring sites

APPENDIX 2:

Relative source contributions of the suspended sediment samples collected at each monitoring site

APPENDIX 3:

Scatter plots illustrating sample distribution around group centroids from the first and second discriminant functions calculated using stepwise DFA

APPENDIX 1:
Summary characteristics of suspended sediment collected at the monitoring sites

Appendix 1.1 Site 1 (Hunton)
Appendix 1.2 Site 2 (Broadward)
Appendix 1.3 Site 3 (Eaton)
Appendix 1.4 Site 4 (Marlbrook)
Appendix 1.5 Site 5 (Lugwardine)

Appendix 1.1 **Summary characteristics of suspended sediment collected at the Hunton monitoring site.**

Sampling period		Weight (g d^{-1}) *	d_{50} (µm)	% > 63 (µm)	% < 63 (µm)	% < 2 (µm)
1	29/04/09 - 23/07/09	0.4	19.2	1.9	98.1	8.4
2	23/07/09 - 09/09/09	0.3	20.0	0.9	99.1	7.5
3	09/09/09 - 11/02/10	2.2	24.6	3.4	96.6	6.8
4	11/02/10 - 08/04/10	0.1	24.2	1.3	98.7	7.5
5	08/04/10 - 31/05/10	0.4	23.0	2.0	98.0	6.6
6	31/05/10 - 09/09/10	0.2	16.3	1.2	98.8	9.4
7	09/09/10 - 25/10/10	3.1	16.6	1.4	98.6	9.6
8	25/10/10 - 06/12/10	0.3	16.2	1.7	98.3	10.3
9	06/12/10 - 31/01/11	1.4	20.4	2.6	97.4	8.8
10	31/01/11 - 09/03/11	0.6	18.6	2.0	98.0	9.3
11	09/03/11 - 21/04/11	0.1	29.8	2.9	97.1	6.0
12	21/04/11 - 24/06/11	0.1	31.7	5.2	94.8	6.2
13	24/06/11 - 17/08/11	0.1	38.7	3.8	96.2	6.0
14	17/08/11 - 28/09/11	0.1	46.8	7.2	92.8	5.2
15	28/09/11 - 08/11/11	0.1	26.3	6.9	93.1	8.4
16	08/11/11 - 21/12/11	2.8	22.0	2.6	97.4	8.0
17	21/12/11 - 09/02/12	2.5	24.2	2.7	97.3	7.3
18	09/02/12 - 09/03/12	0.3	18.9	0.0	100.0	8.8
19	09/03/12 - 17/05/12	2.2	23.0	2.8	97.2	7.9
20	17/05/12 - 28/06/12	0.9	19.6	2.3	97.7	8.4
21	28/06/12 - 09/08/12	2.1	20.0	2.3	97.7	9.0
22	09/08/12 - 24/10/12	1.3	20.0	1.8	98.2	9.2

** sample weight (g d^{-1}) calculated as total weight divided by the total number of days the time integrated sampler was installed in the channel.*

Appendix 1.2 **Summary characteristics of suspended sediment collected at the Broadward monitoring site.**

Sampling period		Weight (g d^{-1}) *	d_{50} (µm)	% > 63 (µm)	% < 63 (µm)	% < 2 (µm)
1	29/04/09 - 23/07/09	1.3	14.3	1.1	98.9	10.9
2	23/07/09 - 09/09/09	1.5	15.1	1.0	99.0	10.4
3	09/09/09 - 11/02/10	0.6	15.7	7.2	92.8	10.0
4	17/03/10 - 31/05/10	0.8	13.9	0.9	99.1	10.9
5	31/05/10 - 07/09/10	0.8	12.8	1.9	98.1	12.2
6	07/09/10 - 21/10/10	2.3	13.4	1.6	98.4	11.8
7	21/10/10 - 06/12/10	1.4	14.6	1.4	98.6	12.3
8	06/12/10 - 31/01/11	9.7	21.2	2.3	97.7	9.1
9	31/01/11 - 09/03/11	1.0	16.3	2.4	97.6	10.2
10	09/03/11 - 21/04/11	0.5	16.8	3.0	97.0	9.9
11	21/04/11 - 24/06/11	0.6	11.1	2.5	97.5	13.6
12	24/06/11 - 17/08/11	0.3	12.5	2.6	97.4	11.4
13	17/08/11 - 28/09/11	0.2	12.0	1.3	98.7	13.9
14	28/09/11 - 08/11/11	0.3	17.1	1.9	98.1	8.1
15	08/11/11 - 30/12/11	0.8	14.4	0.0	100.0	10.5
16	09/02/12 - 09/03/12	1.2	19.1	3.5	96.5	9.3
17	09/03/12 - 22/05/12	0.6	16.5	1.2	98.8	8.2
18	22/05/12 - 09/08/12	0.9	14.5	1.3	98.7	11.6
19	09/08/12 - 30/10/12	0.4	13.0	1.0	99.0	11.1

** sample weight (g d^{-1}) calculated as total weight divided by the total number of days the time integrated sampler was installed in the channel.*

Appendix 1.3 Summary characteristics of suspended sediment collected at the Eaton monitoring site.

Sampling period		Weight (g d^{-1}) *	d_{50} (µm)	% > 63 (µm)	% < 63 (µm)	% < 2 (µm)
1	11/08/09 - 09/09/09	0.3	20.9	2.5	97.5	8.3
2	09/09/09 - 25/02/10	1.5	18.3	1.7	98.3	11.1
3	25/02/10 - 17/03/10	0.4	26.5	2.1	97.9	8.3
4	17/03/10 - 31/05/10	0.2	17.5	0.9	99.1	10.3
5	31/05/10 - 07/09/10	0.2	13.7	2.2	97.8	14.7
6	07/09/10 - 21/10/10	0.3	14.4	0.6	99.4	11.4
7	21/10/10 - 06/12/10	0.1	21.8	1.4	98.6	9.5
8	06/12/10 - 31/01/11	0.5	17.0	2.4	97.6	12.0
9	31/01/11 - 09/03/11	0.5	15.2	1.2	98.8	13.3
10	09/03/11 - 21/04/11	0.2	21.7	5.8	94.2	8.9
11	21/04/11 - 24/06/11	0.3	8.6	3.4	96.6	21.4
12	24/06/11 - 17/08/11	0.1	25.5	8.5	91.5	11.6
13	17/08/11 - 28/09/11	0.1	41.4	5.3	94.7	10.2
14	28/09/11 - 08/11/11	0.1	16.3	4.2	95.8	13.1
15	08/11/11 - 30/12/11	1.9	14.0	1.0	99.0	13.5
16	30/12/11 - 09/02/12	1.7	16.4	1.4	98.6	11.9
17	09/02/12 - 09/03/12	0.3	17.5	5.1	94.9	12.6
18	09/03/12 - 22/05/12	1.9	16.3	3.3	96.7	12.2
19	22/05/12 - 09/08/12	1.8	14.4	1.4	98.6	13.0
20	09/08/12 - 24/10/12	0.9	12.5	0.9	99.1	15.3

** sample weight (g d^{-1}) calculated as total weight divided by the total number of days the time integrated sampler was installed in the channel.*

Appendix 1.4 Summary characteristics of suspended sediment collected at the Marlbrook monitoring site.

Sampling period		Weight (g d^{-1}) *	d_{50} (µm)	% > 63 (µm)	% < 63 (µm)	% < 2 (µm)
1	21/09/09 - 25/02/10	1.9	17.4	1.6	98.4	9.4
2	25/02/10 - 17/03/10	1.3	20.2	3.6	96.4	8.4
3	17/03/10 - 31/05/10	1.5	14.5	1.3	98.7	11.3
4	31/05/10 - 07/09/10	0.1	14.2	1.3	98.7	11.4
5	07/09/10 - 21/10/10	4.3	14.6	1.8	98.2	10.3
6	21/10/10 - 07/12/10	1.2	12.5	1.4	98.6	12.4
7	07/12/10 - 31/01/11	1.0	15.2	2.0	98.0	11.4
8	31/01/11 - 09/03/11	1.3	15.5	2.4	97.6	11.1
9	09/03/11 - 21/04/11	0.2	16.3	1.6	98.4	9.5
10	21/04/11 - 24/06/11	0.2	7.2	3.5	96.5	20.1
11	24/06/11 - 17/08/11	0.1	13.7	0.9	99.1	12.1
12	17/08/11 - 28/09/11	0.1	19.4	2.3	97.7	10.7
13	28/09/11 - 08/11/11	0.2	17.8	2.4	97.6	10.7
14	08/11/11 - 30/12/11	0.8	13.8	1.7	98.3	11.8
15	30/12/11 - 09/02/12	4.0	16.7	1.3	98.7	10.1
16	09/02/12 - 09/03/12	0.1	49.7	0.0	100.0	5.6
17	09/03/12 - 22/05/12	2.2	16.0	0.7	99.3	8.6
18	22/05/12 - 09/08/12	4.4	14.1	0.5	99.5	10.5
19	09/08/12 - 26/10/12	0.3	11.5	0.5	99.5	12.0

** sample weight (g d^{-1}) calculated as total weight divided by the total number of days the time integrated sampler was installed in the channel.*

Appendix 1.5 Summary characteristics of suspended sediment collected at the Lugwardine monitoring site.

Sampling period		Weight (g d^{-1}) *	d_{50} (μm)	% > 63 (μm)	% < 63 (μm)	% < 2 (μm)
1	11/08/09 - 09/09/09	0.9	14.8	1.2	98.8	11.0
2	17/03/10 - 31/05/10	1.1	13.6	0.8	99.2	10.5
3	31/05/10 - 09/09/10	0.7	12.4	0.6	99.4	11.5
4	09/09/10 - 21/10/10	2.9	10.4	0.0	100.0	13.3
5	21/10/10 - 07/12/10	0.8	10.7	0.7	99.3	14.6
6	07/12/10 - 31/01/11	0.8	15.7	1.6	98.4	11.1
7	31/01/11 - 09/03/11	0.7	14.2	3.1	96.9	12.4
8	09/03/11 - 28/04/11	0.04	23.8	0.8	99.2	7.2
9	28/04/11 - 24/06/11	0.4	11.9	2.5	97.5	14.2
10	24/06/11 - 17/08/11	0.2	11.4	2.1	97.9	16.2
11	17/08/11 - 28/09/11	0.1	19.4	2.7	97.3	12.0
12	28/09/11 - 15/11/11	0.4	11.4	2.1	97.9	13.8
13	15/11/11 - 30/12/11	5.2	14.3	1.0	99.0	12.3
14	30/12/11 - 09/02/12	4.9	15.1	1.2	98.8	11.4
15	09/02/12 - 09/03/12	1.0	15.7	3.0	97.0	11.1
16	09/03/12 - 22/05/12	2.6	13.2	1.1	98.9	13.1
17	22/05/12 - 09/08/12	4.7	8.7	0.8	99.2	17.6
18	09/08/12 - 30/10/12	2.5	12.9	0.4	99.6	11.7

** sample weight (g d^{-1}) calculated as total weight divided by the total number of days the time integrated sampler was installed in the channel.*

APPENDIX 2:
Relative source contributions of the suspended sediment samples collected at each monitoring site

Appendix 2.1 Site 1: Hunton

Appendix 2.2 Site 2: Broadward

Appendix 2.3 Site 3: Eaton

Appendix 2.4 Site 4: Marlbrook

Appendix 2.5 Site 5: Lugwardine

Appendix 2.1 Relative source contributions of the suspended sediment samples collected at the Hunton Bridge monitoring site *(highlighted cells show periods when sub-catchments contribute to the sediment load).*

	Sampling period source contributions																				
	29/04/09 - 23/07/09	23/07/09 - 09/09/09	09/09/09 - 11/02/10	11/02/10 - 08/04/10	08/04/10 - 31/05/10	31/05/10 - 09/09/10	09/09/10 - 25/10/10	25/10/10 - 06/12/10	06/12/10 - 31/01/11	31/01/11 - 09/03/11	09/03/11 - 21/04/11	21/04/11 - 24/06/11	24/06/11 - 17/08/11	17/08/11 - 28/09/11	28/09/11 - 08/11/11	08/11/11 - 21/12/11	21/12/11 - 09/02/12	09/02/12 - 09/03/12	09/03/12 - 17/05/12	17/05/12 - 28/06/12	28/06/12 - 09/08/12	09/08/12 - 24/10/12
Arrow Source nr. Blaen-rothrow	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.03	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sychcwm nr. Cnwch	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.00	0.07	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.08	0.14	0.21	0.00	0.00	0.00
Cwm Griffin at Cloggau	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.01	0.11	0.21	0.00	0.23	0.11	0.25	0.00	0.00	0.00	0.00	0.24	0.00	0.00
Glasnant at Veault	0.86	0.84	0.16	0.20	0.77	0.22	0.33	0.40	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00
nr. Dan-yr-allt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.05	0.10	0.13	0.14	0.00	0.00	0.00
Newchurch	0.02	0.01	0.06	0.00	0.00	0.45	0.03	0.22	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.16	0.00	0.28	0.15	0.38	0.29	0.15
Cwmila Brook nr. Gilfach-yr-heol	0.00	0.00	0.54	0.72	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Milton Mill at Milton	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.36	0.23	0.11	0.00	0.09	0.00	0.00	0.18	0.15	0.03	0.15	0.07	0.17	0.23
Wern and Puckmoor Wood nr. The Gaer	0.00	0.00	0.18	0.00	0.06	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
nr. Llanarrow Cottage	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Huntington Park nr. Park Stile Mill	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.15	0.00	0.16	0.03	0.27	0.00	0.08	0.01	0.23	0.00	0.22	0.00	0.17	0.00
nr. Arrow Court	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.64	0.00	0.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
The Toll House nr. Hergest Mill	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.05	0.00	0.00	0.00	0.00	0.00
Headbrook nr. Kington	0.00	0.15	0.06	0.08	0.08	0.30	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Redhill Farm nr. Headbrook	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.00	0.14	0.28	0.32	0.16	0.29	0.00	0.58	0.24	0.16	0.33	0.05	0.14	0.13	0.14
Gilwern Brook at Sunset	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.10	0.08	0.00	0.00	0.00	0.00	0.06	0.23	0.10	0.05	0.03	0.08	0.13	0.01
Rushock and Little Downfield nr. Mill Farm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.13	0.00	0.00	0.00	0.00	0.00	0.09	0.13	0.04	0.05	0.09	0.07	0.47
Shawl nr. Hunton bridge	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.17	0.12	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Appendix 2.2 Relative source contributions of the suspended sediment samples collected at the Broadward Farm monitoring site *(highlighted cells show periods when sub-catchments contribute to the sediment load).*

	Sampling period source contributions																			
	29/04/09 - 23/07/09	23/07/09 - 09/09/09	09/09/09 - 11/02/10	17/03/10 - 31/05/10	31/05/10 - 07/09/10	07/09/10 - 21/10/10	21/10/10 - 06/12/10	06/12/10 - 31/01/11	31/01/11 - 09/03/11	09/03/11 - 21/04/11	21/04/11 - 24/06/11	24/06/11 - 17/08/11	17/08/11 - 28/09/11	28/09/11 - 08/11/11	08/11/11 - 30/12/11	30/12/11 - 09/02/12	09/02/12 - 09/03/12	09/03/12 - 22/05/12	22/05/12 - 09/08/12	09/08/12 - 30/10/12
Glasnant at Veault	0.37	0.41	0.18	0.37	0.34	0.15	0.25	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Newchurch	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00
Milton Mill at Milton	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.08	0.00	0.00	0.00	0.00	0.00
The Toll House nr. Hergest Mill	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00
Headbrook nr. Kington	0.00	0.00	0.03	0.00	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gilwern Brook	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.12	0.05	0.02	0.00	0.00	0.11	0.00	0.00	0.00	0.00
Rushock and Little Downfield nr. Mill Farm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.15	0.14	0.02	0.00
The Larches nr. Hunton Bridge	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.08	0.22	0.20	0.26	0.23	0.00	0.08	0.12	0.18	0.10	0.11
Mowley Wood nr. Lower Tan House	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.14	0.13	0.03	0.00	0.00	0.09	0.00	0.48	0.00	0.00	0.00	0.00	0.00
Curl Brook	0.21	0.08	0.16	0.24	0.02	0.07	0.43	0.20	0.00	0.00	0.00	0.00	0.00	0.29	0.00	0.00	0.30	0.24	0.06	0.25
nr. Broome Farm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
nr. Little Broome	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lyme Green nr. Nun House Farm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00
Lawton marsh nr. Lawton	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.09	0.07	0.04	0.24	0.00	0.08	0.00	0.10	0.13	0.09	0.07	0.34
Moor Brook	0.11	0.08	0.17	0.00	0.00	0.19	0.00	0.11	0.22	0.00	0.00	0.00	0.16	0.00	0.10	0.00	0.10	0.05	0.00	0.13
Stagbatch nr. Monkland	0.00	0.04	0.10	0.00	0.06	0.05	0.00	0.02	0.02	0.20	0.00	0.00	0.00	0.00	0.15	0.08	0.00	0.00	0.01	0.00
Stretford Brook	0.31	0.35	0.20	0.31	0.40	0.17	0.32	0.05	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.16	0.13
Ivington Common nr. Newtown	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.08	0.07	0.08	0.19	0.00	0.00	0.00	0.08	0.14	0.20	0.26	0.53	0.00
Honeylake Brook	0.00	0.04	0.16	0.08	0.17	0.29	0.00	0.27	0.31	0.42	0.43	0.51	0.44	0.40	0.11	0.28	0.00	0.02	0.00	0.04

Appendix 2.3 Relative source contributions of the suspended sediment samples collected at the Eaton Hall Farm monitoring site *(highlighted cells show periods when sub-catchments contribute to the sediment load).*

	Sampling period source contributions																			
	11/08/09 - 09/09/09	09/09/09 - 25/02/10	25/02/10 - 17/03/10	17/03/10 - 31/05/10	31/05/10 - 07/09/10	07/09/10 - 21/10/10	21/10/10 - 06/12/10	06/12/10 - 31/01/11	31/01/11 - 09/03/11	09/03/11 - 21/04/11	21/04/11 - 24/06/11	24/06/11 - 17/08/11	17/08/11 - 28/09/11	28/09/11 - 08/11/11	08/11/11 - 30/12/11	30/12/11 - 09/02/12	09/02/12 - 09/03/12	09/03/12 - 22/05/12	22/05/12 - 09/08/12	09/08/12 - 24/10/12
Lugg source	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.11	0.00
nr. Lanlluest	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00
Nant Yr Wyn nr. Crug Bridge	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.00	0.00	0.00	0.00
Crungoed	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.01	0.00	0.00	0.00	0.00
nr. Lea Hall Farm	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.02	0.00	0.00
Pye Corner	0.00	0.00	0.00	0.00	0.00	0.05	0.13	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
nr. Lower Bailey and Bailey Farm	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.04	0.11	0.10	0.00	0.07	0.00	0.05	0.00	0.02	0.49	0.00	0.00	0.39
nr. Griffin Lloyd	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.16	0.08	0.37	0.00	0.00	0.00	0.07	0.08	0.00	0.00	0.00	0.30
nr. Treburvaugh	0.00	0.00	0.00	0.00	0.00	0.06	0.04	0.15	0.15	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.02	0.14	0.15	0.00
Pilleth	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.26	0.00	0.00	0.00	0.00	0.00	0.22	0.23	0.00
Cwm Blewyn at Nant-y-groes	0.08	0.11	0.01	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cwm Whitton at Whitton	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.02	0.00
Cascob Brook	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.00	0.00
Boultibrooke Bridge nr. Willowbrook	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00
Lugg Bridge at Presteigne	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.01	0.00	0.00	0.00	0.00
nr. Rosser's Bridge	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
nr. Kinsham Cross	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00
Lime Brook at Lower Yeld	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.05	0.12	0.00
nr. Shirley Farm from Shirley Wood	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.07	0.06	0.00	0.00	0.00
nr. Mortimer's Cross from Lucton	0.00	0.00	0.00	0.00	0.00	0.17	0.32	0.16	0.22	0.30	0.30	0.32	0.24	0.15	0.23	0.15	0.18	0.15	0.14	0.00
nr. Gilbert's Farm and Aston	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.24	0.00	0.00	0.02	0.00
Blue Ditch nr. Mousenatch Farm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00
Pinsley Brook	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00
Ridgemoor Brook	0.34	0.45	0.59	0.32	0.51	0.62	0.32	0.26	0.09	0.21	0.00	0.02	0.71	0.71	0.10	0.04	0.13	0.00	0.00	0.00
Cheaton Brook	0.58	0.44	0.40	0.64	0.49	0.02	0.13	0.25	0.27	0.28	0.33	0.33	0.05	0.08	0.05	0.14	0.12	0.20	0.21	0.31

Appendix 2.4 Relative source contributions of the suspended sediment samples collected at the Marlbrook Farm monitoring site *(highlighted cells show periods when sub-catchments contribute to the sediment load).*

	Sampling period source contributions																		
	21/09/09 - 25/02/10	25/02/10 - 17/03/10	17/03/10 - 31/05/10	31/05/10 - 07/09/10	07/09/10 - 21/10/10	21/10/10 - 07/12/10	07/12/10 - 31/01/11	31/01/11 - 09/03/11	09/03/11 - 21/04/11	21/04/11 - 24/06/11	24/06/11 - 17/08/11	17/08/11 - 28/09/11	28/09/11 - 08/11/11	08/11/11 - 30/12/11	30/12/11 - 09/02/12	09/02/12 - 09/03/12	09/03/12 - 22/05/12	22/05/12 - 09/08/12	09/08/12 - 26/10/12
Nant Yr Wyn nr. Crug Bridge	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Crungoed	0.00	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00
nr. Lea Hall Farm	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.07	0.01	0.00
Pye Corner	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.04	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
nr. Lower Bailey and Bailey Farm	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.12	0.05	0.16	0.18	0.19	0.19	0.03	0.06	0.08	0.00	0.00	0.06
nr. Griffin Lloyd	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.00	0.04	0.07	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.26
nr. Treburvaugh	0.00	0.00	0.00	0.00	0.09	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.13	0.00
Pilleth	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cascob Brook nr. The Grove	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.03	0.00
Lugg Bridge at Presteigne	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.00
nr. Kinsham Cross	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00
Lime Brook at Lower Yeld	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
nr. Mortimer's Cross from Lucton	0.00	0.00	0.00	0.00	0.17	0.05	0.07	0.21	0.00	0.00	0.00	0.00	0.00	0.21	0.05	0.00	0.03	0.07	0.05
nr. Gilbert's Farm and Aston	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pinsley Brook nr. Wegnalls Farm	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ridgemoor Brook	0.01	0.05	0.21	0.71	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.12	0.00	0.00	0.30	0.73	0.00	0.04	0.00
Cheaton Brook	0.00	0.19	0.00	0.00	0.15	0.07	0.05	0.21	0.23	0.17	0.52	0.50	0.34	0.00	0.07	0.01	0.04	0.07	0.32
Sychcwm nr. Cnwch	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00
Glasnant at Veault	0.17	0.26	0.27	0.29	0.06	0.27	0.09	0.23	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
nr. Dan-yr-allt	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.01	0.00
Newchurch	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00
Headbrook nr. Kington	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.01	0.00	0.00	0.03	0.00
Redhill Farm nr. Headbrook	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00
The Larches nr. Hunton Bridge	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.12	0.09	0.17	0.10	0.16	0.16	0.02	0.03	0.11	0.06	0.04
Curl Brook	0.40	0.00	0.52	0.00	0.00	0.01	0.12	0.00	0.05	0.06	0.00	0.00	0.00	0.11	0.18	0.00	0.00	0.00	0.04
nr. Little Broome	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lyme Green nr. Nun House Farm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00
Lawton marsh nr. Lawton	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.10	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14
Moor Brook	0.17	0.15	0.00	0.00	0.21	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.00	0.00	0.16	0.04	0.00
Stretford Brook	0.20	0.33	0.00	0.00	0.00	0.16	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.00
Honeylake Brook	0.00	0.00	0.00	0.00	0.00	0.15	0.05	0.03	0.00	0.00	0.00	0.00	0.00	0.06	0.05	0.00	0.13	0.15	0.00
Brierley Cut nr. Elms Green	0.00	0.00	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Marl Brook	0.00	0.00	0.00	0.00	0.04	0.00	0.08	0.04	0.28	0.29	0.12	0.04	0.31	0.14	0.00	0.15	0.07	0.00	0.09

Appendix 2.5 Relative source contributions of the suspended sediment samples collected at the Lugwardine monitoring site *(highlighted cells show periods when sub-catchments contribute to the sediment load).*

	Sampling period source contributions																	
	11/08/09 - 09/09/09	17/03/10 - 31/05/10	31/05/10 - 09/09/10	09/09/10 - 21/10/10	21/10/10 - 07/12/10	07/12/10 - 31/01/11	31/01/11 - 09/03/11	09/03/11 - 28/04/11	28/04/11 - 24/06/11	24/06/11 - 17/08/11	17/08/11 - 28/09/11	28/09/11 - 15/11/11	15/11/11 - 30/12/11	30/12/11 - 09/02/12	09/02/12 - 09/03/12	09/03/12 - 22/05/12	22/05/12 - 09/08/12	09/08/12 - 30/10/12
Nant Yr Wyn nr. Crug Bridge	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.04	0.00	0.00	0.00	0.00
nr. Lea Hall Farm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.01	0.00	0.11	0.00	0.00
Pye Corner	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.00	0.00
nr. Lower Bailey and Bailey Farm	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.05	0.06	0.10	0.13	0.05	0.01	0.01	0.09	0.00	0.00	0.14
nr. Griffin Lloyd	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
nr. Treburvaugh	0.00	0.00	0.00	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.08
Pilleth	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00
Cascob Brook	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.05	0.00
Discoed	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lugg Bridge at Presteigne	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00
nr. Kinsham Cross	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.12	0.00	0.00	0.00	0.00
nr. Shirley Farm from Shirley Wood	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
nr. Mortimer's Cross from Lucton	0.00	0.00	0.00	0.04	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.05	0.24	0.00	0.01	0.00	0.07	0.00
nr. Gilbert's Farm and Aston	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.11	0.00	0.00	0.00	0.00
Ridgemoor Brook	0.00	0.14	0.17	0.00	0.00	0.00	0.00	0.13	0.01	0.11	0.00	0.06	0.21	0.02	0.10	0.00	0.00	0.09
Cheaton Brook	0.00	0.12	0.01	0.02	0.08	0.11	0.06	0.21	0.00	0.00	0.00	0.00	0.02	0.13	0.05	0.09	0.24	0.17
Sychcwm nr. Cnwch	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.05	0.07	0.00
Glasnant at Veault	0.26	0.27	0.41	0.16	0.34	0.08	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
nr. Dan-yr-allt	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.04	0.00
Newchurch	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00
Back Brook	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
The Larches nr. Hunton Bridge	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.07	0.02	0.00	0.06	0.05	0.00
Curl Brook	0.18	0.07	0.07	0.20	0.18	0.10	0.00	0.00	0.00	0.21	0.00	0.00	0.00	0.00	0.26	0.17	0.02	0.20
Lyme Green nr. Nun House Farm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00
Lawton marsh nr. Lawton	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04
Moor Brook	0.00	0.00	0.10	0.12	0.00	0.00	0.00	0.00	0.23	0.22	0.30	0.10	0.00	0.14	0.10	0.08	0.00	0.00
Stretford Brook	0.30	0.40	0.22	0.25	0.24	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Honeylake Brook	0.00	0.00	0.00	0.05	0.12	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Marl Brook	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.06	0.00
Humber Brook	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.00	0.00	0.03	0.00	0.00	0.00	0.00
nr. Saffron's Cross	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00
Bodenham Brook	0.00	0.00	0.00	0.00	0.00	0.04	0.28	0.00	0.00	0.00	0.00	0.23	0.08	0.04	0.00	0.00	0.00	0.00
Moreton Brook	0.00	0.00	0.00	0.04	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00
Wellington Brook	0.06	0.00	0.00	0.00	0.04	0.00	0.18	0.26	0.33	0.23	0.41	0.13	0.09	0.00	0.03	0.06	0.00	0.07
Little Lugg	0.00	0.00	0.00	0.07	0.00	0.00	0.20	0.00	0.21	0.13	0.00	0.26	0.10	0.11	0.22	0.21	0.20	0.21
nr. Lugwardine	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.02	0.00	0.00	0.00	0.00

APPENDIX 3:
Scatter plots illustrating sample distribution around group centroids from the first and second discriminant functions calculated using stepwise DFA

Appendix 3.1 Cheaton Brook

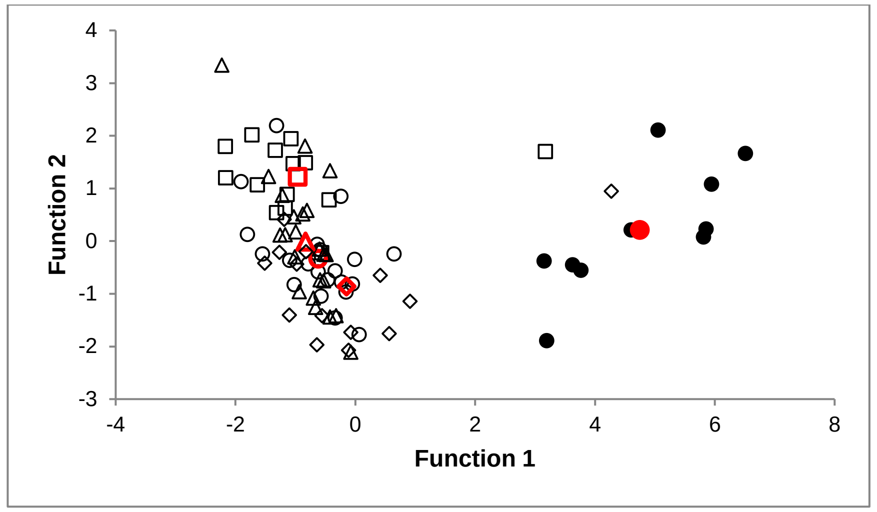
Appendix 3.2 Ridgemoor Brook

Appendix 3.3 Curl Brook

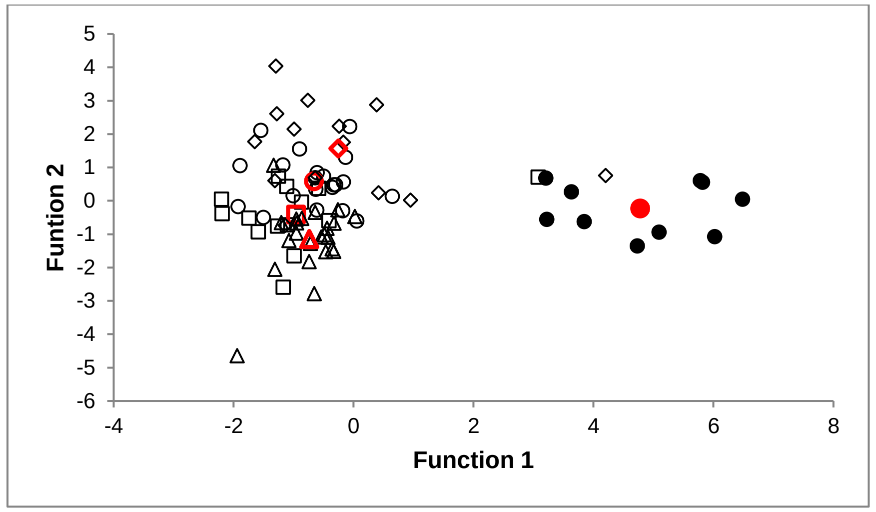
Appendix 3.4 Moor Brook

Appendix 3.1 Scatter plots illustrating sample distribution around group centroids from the first and second discriminant functions calculated using stepwise DFA for the Cheaton Brook sub-catchment.

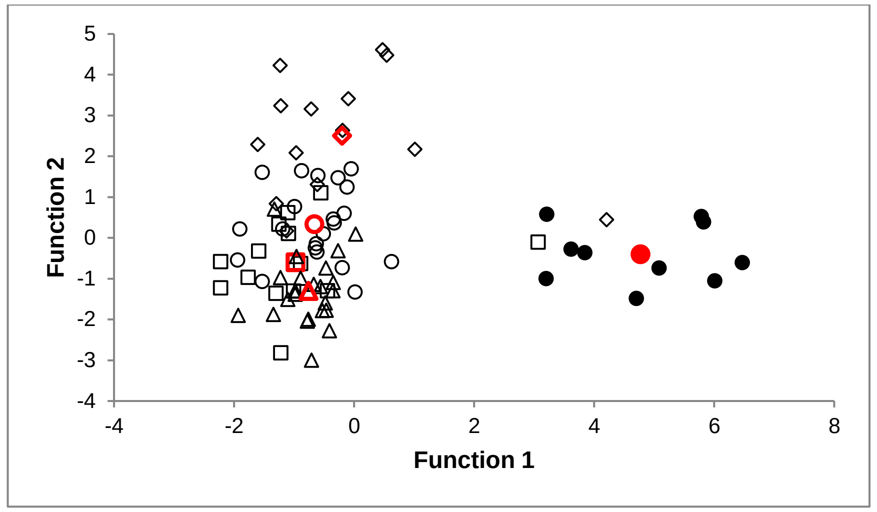
a) Mg, Cr



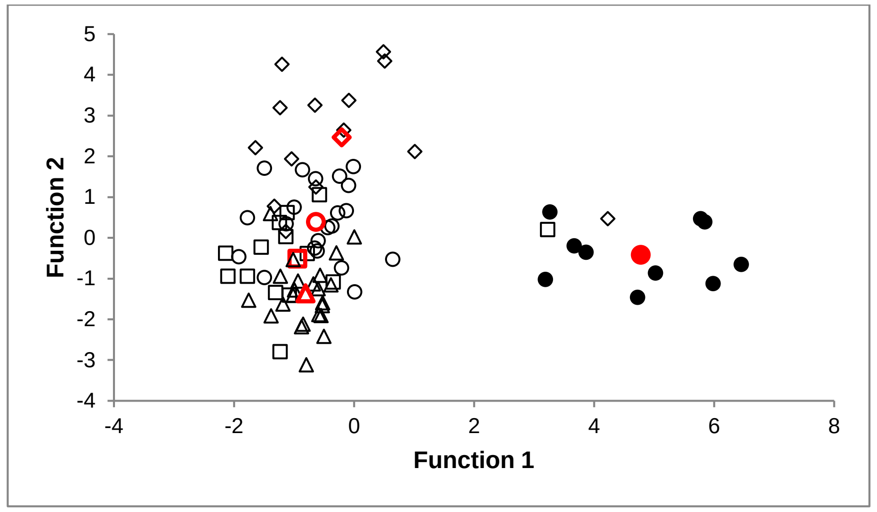
b) Mg, Cr, Mo



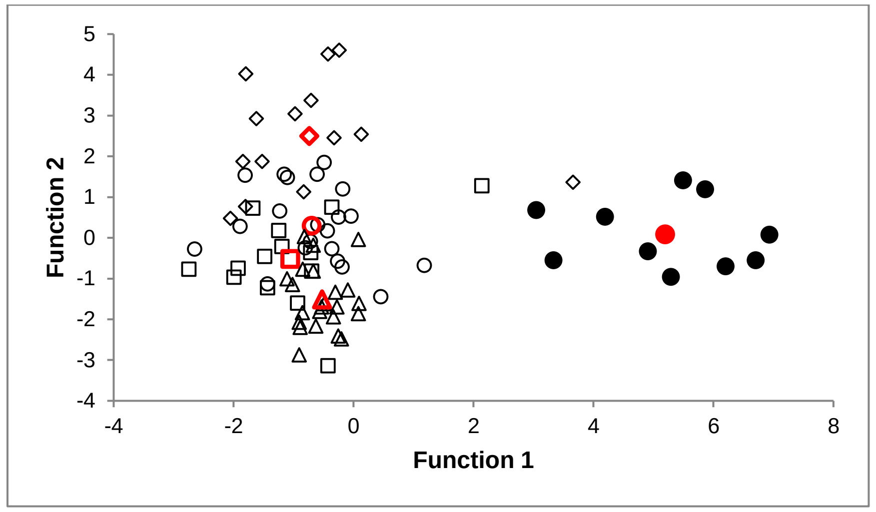
c) Mg, Cr, Mo, Ba



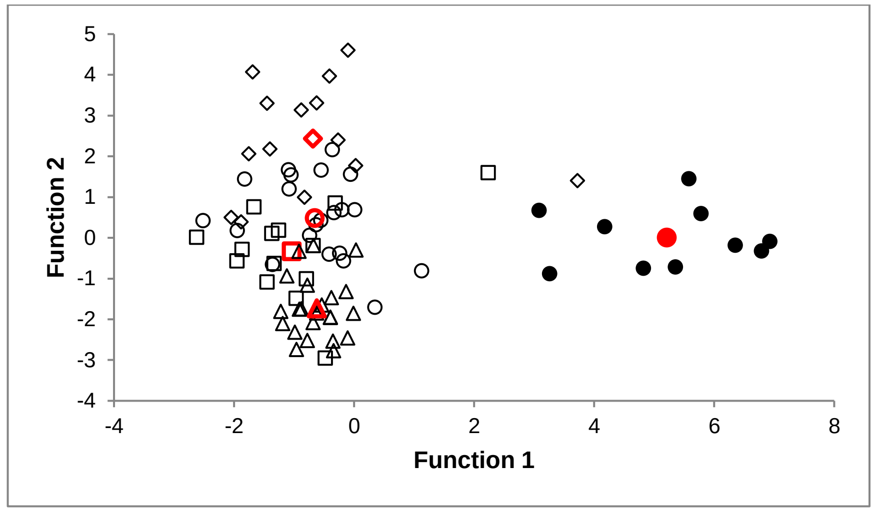
d) Mg, Cr, Mo, Ba, V



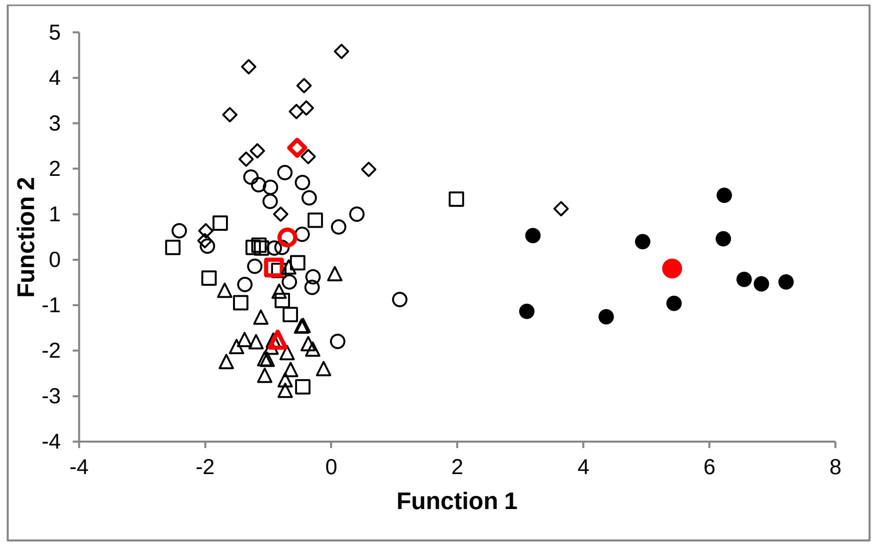
e) Mg, Cr, Mo, Ba, V, Al



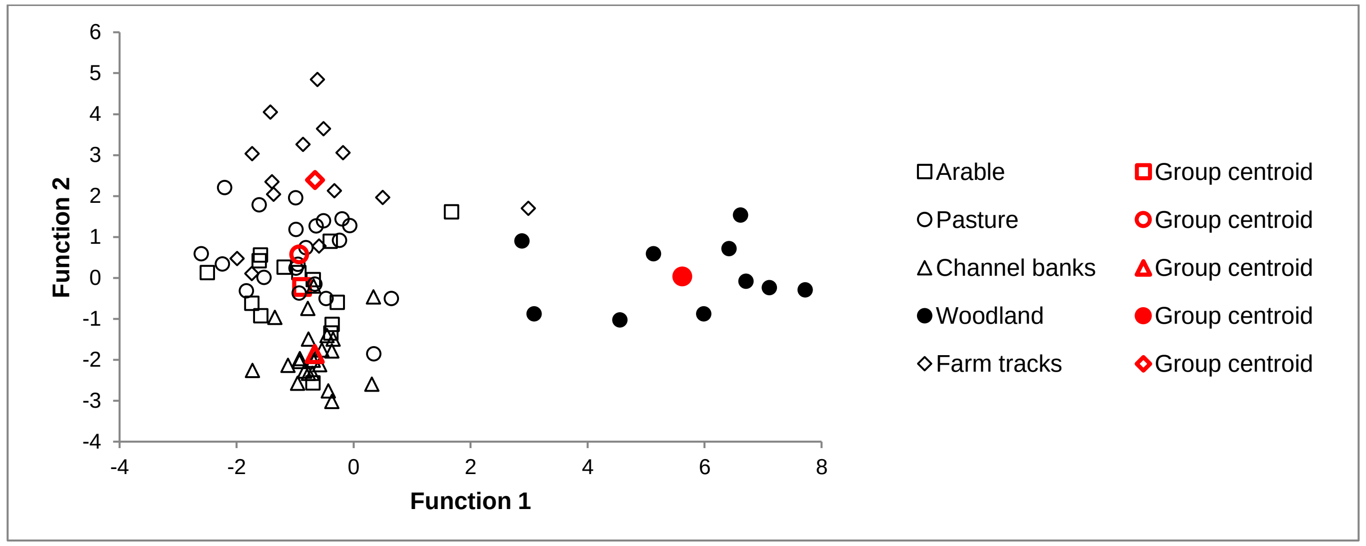
f) Mg, Cr, Mo, Ba, V, Al, Fe



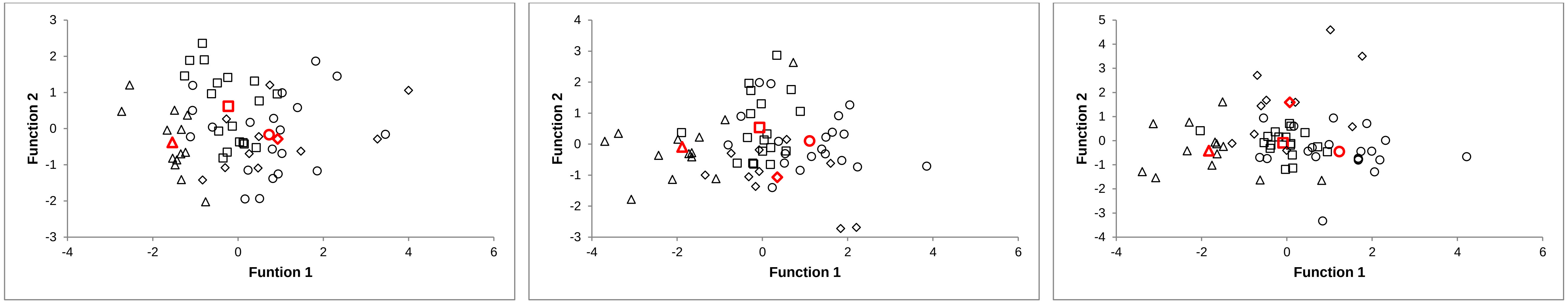
g) Mg, Cr, Mo, Ba, V, Al, Fe, Pb



h) Mg, Cr, Mo, Ba, V, Al, Fe, Pb, Ag

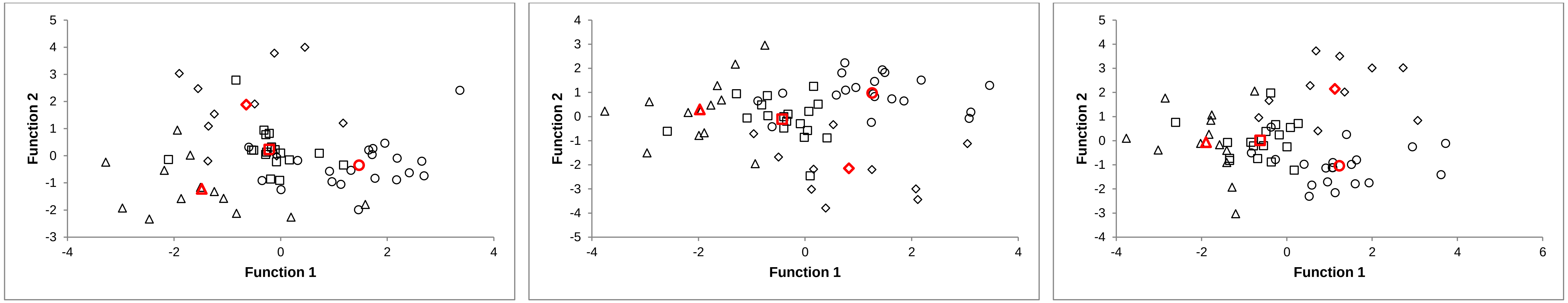


Appendix 3.2 Scatter plots illustrating sample distribution around group centroids from the first and second discriminant functions calculated using stepwise DFA for the Ridgemoor Brook sub-catchment.


a) Mo, Fe

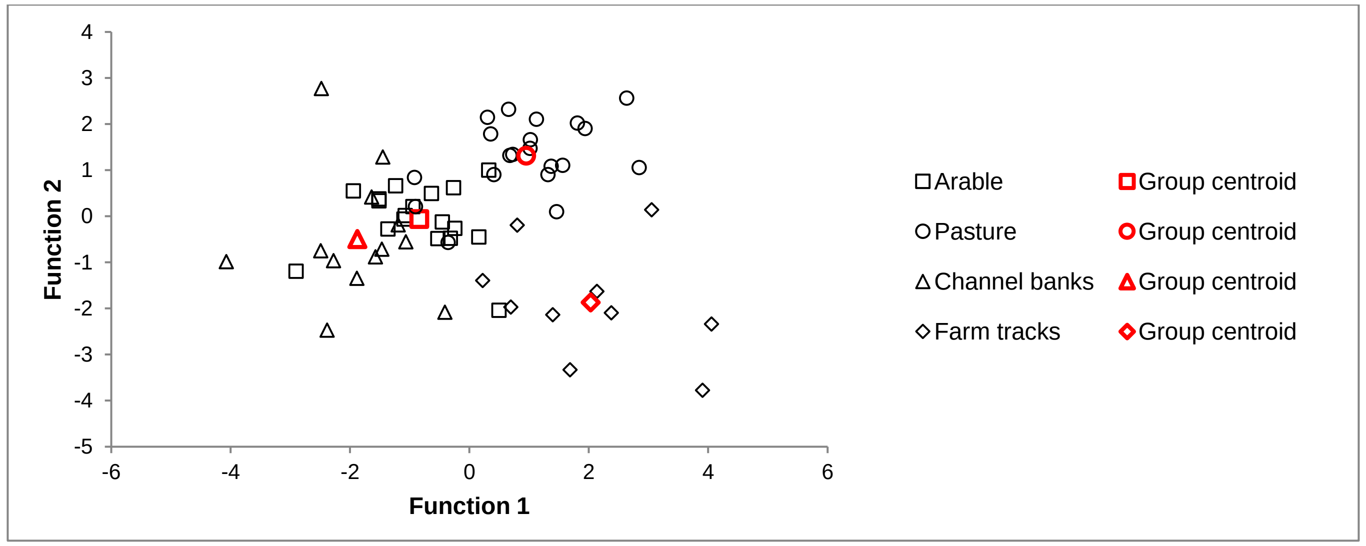
b) Mo, Fe, Cr

c) Mo, Fe, Cr, V

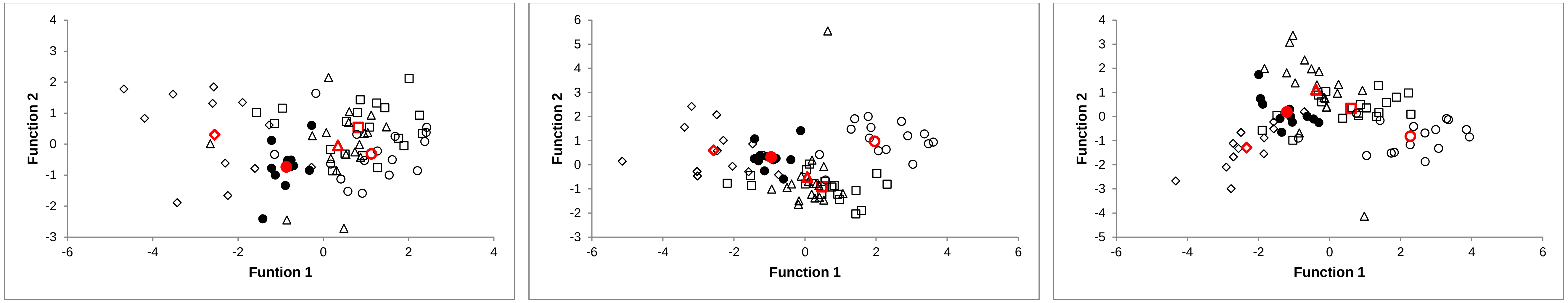

d) Mo, Fe, Cr, V, Al

e) Mo, Fe, Cr, V, Al, K

f) Mo, Fe, Cr, V, Al, K, Pb

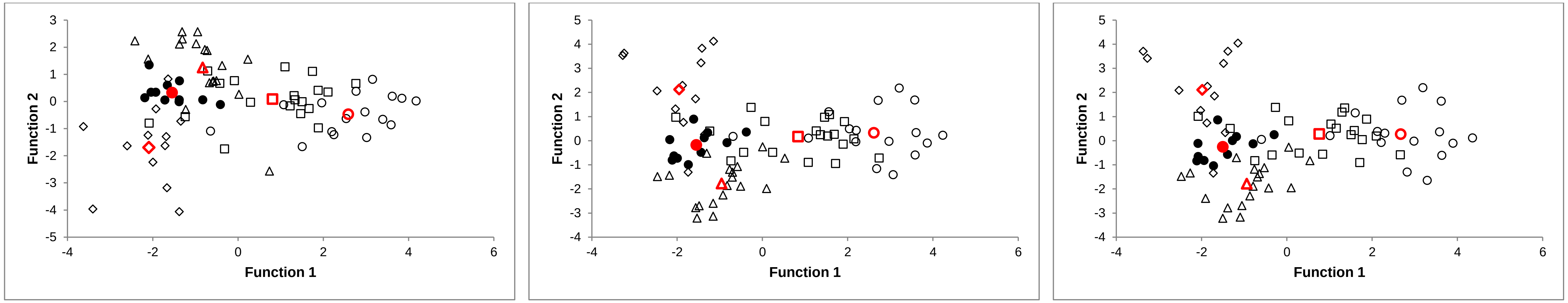

g) Mo, Fe, Cr, V, Al, K, Pb, Zn

Appendix 3.3 Scatter plots illustrating sample distribution around group centroids from the first and second discriminant functions calculated using stepwise DFA for the Curl Brook sub-catchment.


a) Al, V

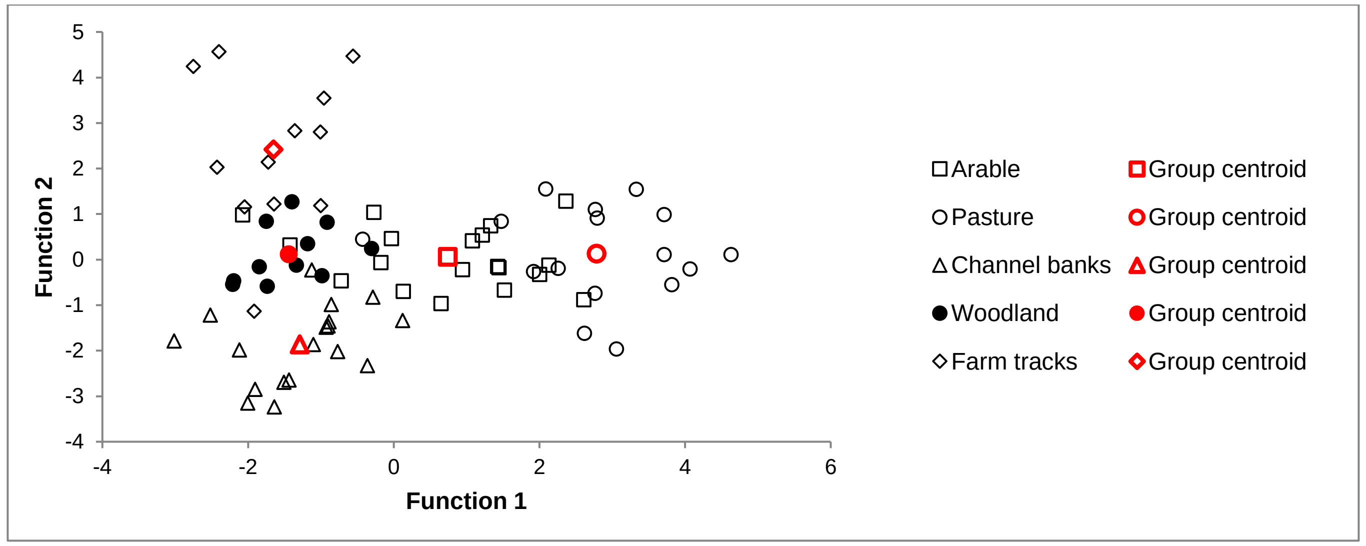
b) Al, V, Zn

c) Al, V, Zn, Ni


d) Al, V, Zn, Ni, Mg

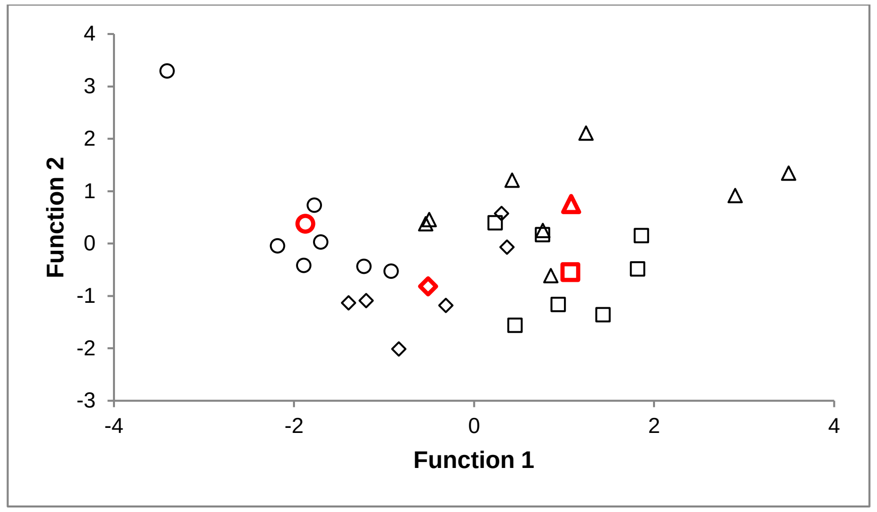
e) Al, V, Zn, Ni, Mg, Mo

f) Al, V, Zn, Ni, Mg, Mo, Cr

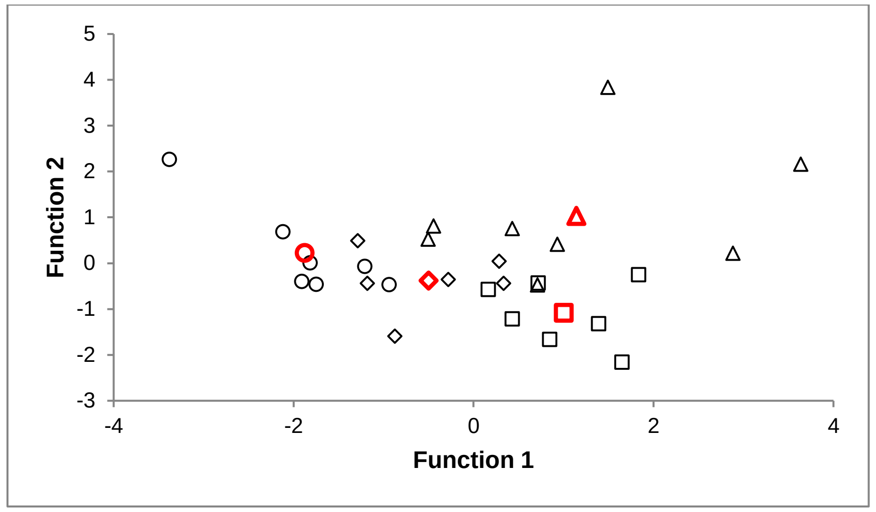

g) Al, V, Zn, Ni, Mg, Mo, Cr, Cd

Appendix 3.4 Scatter plots illustrating sample distribution around group centroids from the first and second discriminant functions calculated using stepwise DFA for the Moor Brook sub-catchment.

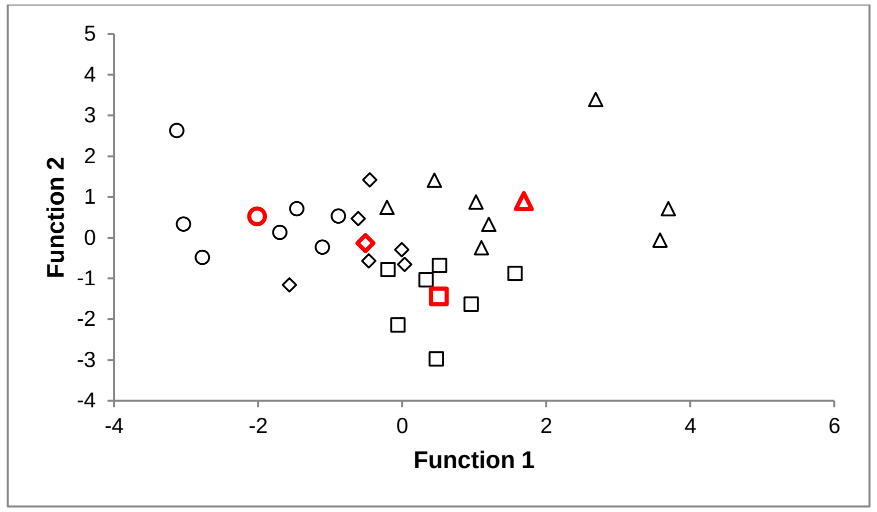
a) Al, Cu



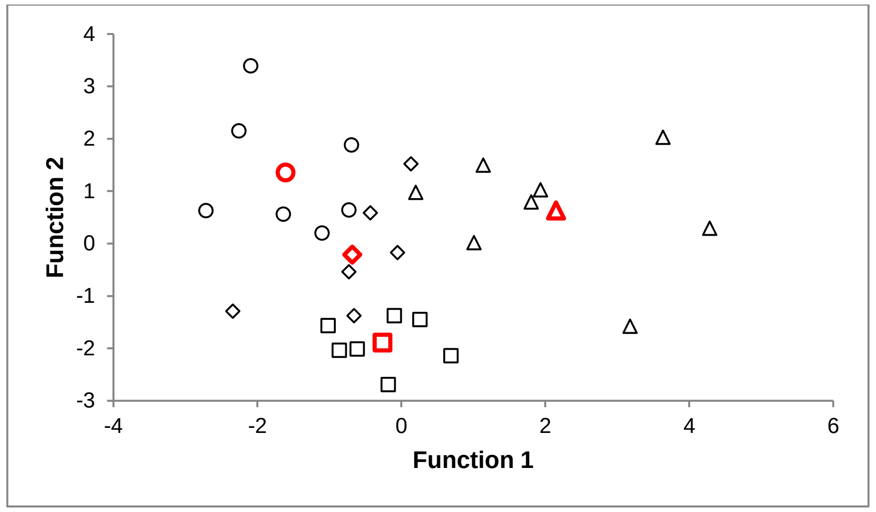
b) Al, Cu, Ba



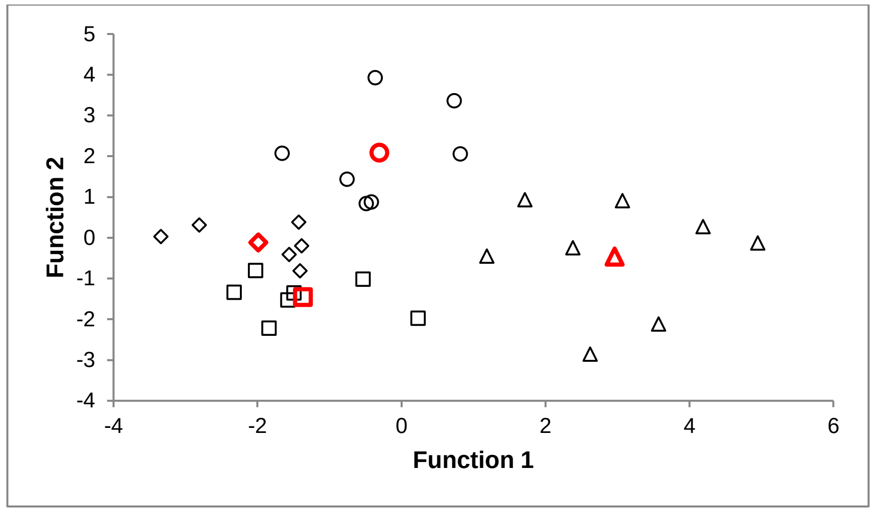
c) Al, Cu, Ba, Cd



d) Al, Cu, Ba, Cd, Ni



e) Al, Cu, Ba, Cd, Ni, Mg



f) Al, Cu, Ba, Cd, Ni, Mg, V