The transport and retention of fine sediments in seasonally vegetated lowland streams

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ABSTRACT

The oversupply of fine sediment to lowland streams has been associated with the general degradation of their habitats with symptoms including increased turbidity, decreases in groundwater to surface water exchange and a decline in biodiversity and Salmonid fecundity. Aquatic macrophytes have been implicated as a factor in fine sediment problems, due to their high capacity for localised fine sediment retention caused by macrophyte patches decreasing channel flow velocities. However, there are still gaps in current knowledge relating to seasonal macrophyte growth and the cycling of fine sediment within lowland streams.

The objectives of this interdisciplinary study were to: (1) investigate the influence of changing seasonal macrophyte cover on fine sediment deposition and storage at the reach scale; (2) analyse the impact of changing seasonal macrophyte cover on fine sediment transport at the reach scale, and (3) examine the temporal and spatial changes of fine sediment deposits, including particle characteristics within *Ranunculus* patches.

Two chalk stream reaches within the Frome-Piddle catchment were chosen for a two year comparison of two similar streams. The distribution and particle characteristics of deposited fine sediment were analysed at the reach scale using monthly site surveys and fine sediment samples taken within *Ranunculus* patches at both sites. Seasonal reach scale releases of corn pollen as fine sediment analogues were used to investigate fine sediment particle transport through both reaches in relation to concurrent changes of macrophyte cover and channel porosity. Lastly, three *Ranunculus* patches were investigated at the patch-scale at both sites over an annual cycle. Investigations were conducted to analyse variations in the volume of deposited and retained fine sediment and particle characteristics within and between patches and within patches in relation to seasonal patch growth.

Fine sediment deposits were found within in-channel macrophytes and marginal vegetation, with considerable deposits found within the margins at both sites but particularly within *Nasturtium* and *Apium* patches on the Bere Stream. Statistical differences were found in the depth of fine sediment within emergent and submergent *Ranunculus* patches at both sites. Fine sediment samples from *Ranunculus* patches were dominated by sand-sized (63-1000 μm) particles in both effective and absolute

fractions, with smaller volumes (<10 %) of silt and clay-sized particles. No correlation was found between the seasonal cover of aquatic macrophytes and corresponding values for the transport (F_X) and loss (K_P) of corn pollen particles. However, corn pollen particles in transport were found to decrease dramatically in number when a combination of factors occurred together. The main influencing factors were the seasonal peak in macrophyte cover, seasonally low channel discharge and high values of channel roughness represented by Manning's N values. Estimated values of channel porosity were not associated with corn pollen transport and retention. Values of corn pollen transport distance (S_P) and depositional velocity (V_{dep}) were not associated with macrophyte cover or channel porosity. Fine sediment was found to be generally distributed within the rooted area of *Ranunculus* patches, with fine sediment deposited in the tail section in the summer months. The head zone of the *Ranunculus* patches were found to possess lower D_{50} values for fine sediment particle size at both sites, other than this there was little differentiation between all of sections within patches.

The results from this study suggest that further development of a holistic approach to aquatic macrophyte management is required within some lowland streams to promote a sustainable balance for fine sediment transport. Future management involving localised weed-cuts should address problems with fine sediment and flow conveyance while also being considerate to habitat ecology and biodiversity.

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ABBREVIATIONS & SYMBOLS

φ – Channel porosity at the reach scale measured as a value between 0 and 1.

%SC – The percentage of silt and clay sized particles within the volume of a fine sediment sample, measured using a Laser coulter counter.

%OM – The percentage of organic matter within a fine sediment sample measured by loss on ignition

ANOVA – Analysis of Variance

BD – Dry bulk density (kg m^3) of a fine sediment sample

BS – Bere Stream at Snatford Bridge

CP – Corn pollen

CPOM – Coarse Particulate Organic Matter (>1000 µm)

CW – Mean channel width

D_{50} – The median particle size of a sediment particle distribution

***d.f.* –** Degrees of freedom within a statistical test

EC – Electrical conductivity (µS cm^{-1})

EDM – Electronic Distance Measurement system

ESD – Sediment depth (cm) within emergent *Ranunculus* patches

EWV – Water flow velocities (m s^{-1}) within emergent *Ranunculus* patches

FPOM – Fine particulate organic matter (0.45-1000 µm)

F_0 – Estimated number of released sediment particles

FV – The River Frome at Frome Vauchurch

F_X – Sediment particle transport efficiency, expressed as a number or percentage

F_Y – Sediment particle retention efficiency, expressed as a number or percentage

GIS – Geographical Information System

GPS – Global Positioning System

h - Mean water depth (m)

IDW - Inverse distance weighting interpolation in ArcGIS

K_P – Longitudinal loss rate (m^{-1}) of released sediment particles

LISST – Laser In-Situ Scattering and Transmissiometry

LSD – Fishers Least Significant Difference test, a type of multiple comparison statistical test used *post-hoc* to determine which groups are significantly different to one another

MSS conc. – Mean rate of suspended sediment (mg l^{-1}) over 24 hours

MV – Marginal vegetation, which may grow from margins into the channel; this excludes *Nasturtium* on the Bere Stream.

NSD – Sediment depth (cm) within *Nasturtium* (water cress) patches

NTT – Nominal transport time (s)

NWV – Water flow velocities (m s^{-1}) within *Nasturtium* (water cress) patches

OSD – Sediment depth (cm) within open (unvegetated) areas

OTD – Total water depth (m) within open (unvegetated) areas

OWV – Water velocities (m s^{-1}) within open (unvegetated) areas

P – Rouse number, a dimensionless number that characterises the way sediment loads are transported.

Q – Discharge (l s^{-1} and m^3 s^{-1})

RSD – Sediment depth (cm) within *Ranunculus* (water crowfoot) patches

RWV – Water flow velocities (m s^{-1}) within *Ranunculus* (water crowfoot) patches

S_0 – Sediment sorting coefficient (Trask Equation), values are between 0 and 1.

SD – Fine sediment depth (cm and m) or standard deviation.

SE – Standard error

S_P – Mean transport distance (m) of released corn pollen

SSD - Sediment depth (cm) within submergent *Ranunculus* patches

SSSI - Site of Special Scientific Interest

ST DS – Rate of suspended sediment (kg d^{-1}) supplied to the downstream section of the reach

ST US – Rate of suspended sediment (kg d^{-1}) supplied to the upstream section of the reach

SWV – Water flow velocities (m s^{-1}) within submerged *Ranunculus* patches

T – Mean time in suspension (s) for released sediment particles (corn pollen)

TV – Total vegetation cover, expressed as a percentage of the area of the river bed

VBD - Vegetated bottom depth (m), the depth between the gravel bed and the bottom of the floating plant

V_{dep} – Depositional velocity (mm s^{-1}) of released sediment particles

V_{fall} – The fall velocity (mm s^{-1}) of released sediment particles

VFPOM – Very Fine Particulate Organic Matter (15-53 µm)

VSD – Sediment depth (cm) within vegetated areas

V_T – Total volume (m^3) of the channel from the gravel to the waters' surface relating to the porosity equation

VTD - Vegetated top depth (m), or Total depth (m) within vegetation

V_V – Volume (m^3) of the void space (porosity equation)

V_w - Mass coefficient of water is calculated by multiplying **α** (coefficient of exchange between free- flowing and storage zones) by water depth in order to express water parcel movement from the channel to transient storage habitats in units of distance per unit time

VWD - Vegetated water depth (m), or water depth in vegetated patches of the channel.

VWV – Water flow velocities (m s^{-1}) within vegetated areas

UFPOM – Ultra Fine Particulate Organic Matter (0.45-15 μm)

UKBAP – United Kingdom Biodiversity Action Plan

U_W - Mean water velocity (m s^{-1})

W: D – Width to depth ratio (m: m) of the channel.

CHAPTER 1

Introduction

Fine sediment (<2 mm) is a natural component of streams and important for their physical habitat and ecosystem functioning. However, the oversupply of fine sediment to lowland rivers and streams is a management problem that has existed for many hundreds of years (Park, 1981). This oversupply of sediment has been the focus of previous research but there has been a growing interest in the issues of and there has been a recurrent focus on fine sediments-related problems within the rivers and streams of Europe and other parts of the world, in part due to recent changes in environmental legislation such as the EU Water Framework Directive.

It has been suggested that the increase in fine sediment supply to rivers and streams is mostly the result of human activities within river and stream catchments (Dolan *et al*., 1974; Wood and Armitage, 1997). Common disturbances leading to increased fine sediment supply include changes in agricultural practices (Owens *et al*., 2005; Walling *et al*., 2006), changes in forestry management (Clews and Ormerod, 2010; Meade, 1982; Wood and Armitage, 1997), the construction of roads (Carter *et al*., 2003; Foltz *et al*., 2008; Owens *et al*., 2005), mining within river catchments (Davies-Colley *et al*., 1992; Owens *et al*., 2005; Read *et al*., 1991), the building of reservoirs and flow management (Boon, 1988; Dolan *et al*., 1974; Holliday *et al*., 2008; Petts *et al*., 1993; Petts, 1988), drainage from residential areas and new building developments (Owens *et al*., 2005), poaching by livestock (Walling and Amos, 1999) and inputs from watercress farms and sewage farms (Owens *et al*., 2005; Walling *et al*., 2006).

The over-abstraction of groundwater from aquifers for human consumption, crop irrigation and providing water for livestock has been previously cited as a common detrimental impact on river flows (Bradford, 2002; Sear *et al*., 1999; Smakhtin, 2001; Walling and Amos, 1999; Walling *et al*., 2006). It has been suggested that decreases in channel flow and discharge caused by over-abstraction have also been associated with increases in deposited and suspended fine sediment loads (Heywood and Walling, 2003; Malmqvist and Rundle, 2002; Matthaei *et al*., 2010; Walling and Amos, 1999; Walling *et al*., 2006; Wharton *et al*., 2006).

In response to this issue the UK Environment Agency and regional water companies have sought to work together to reduce or restrict water abstraction activities within some river catchments. Drought plans have been created by the UK Environment Agency for all regions within the UK (Environment Agency, 2011a), with the additional creation of Catchment Abstraction Management Strategy (CAMS) within some river catchments. An example of a CAMS can be found for the Frome-Piddle catchment in Dorset, England (Environment Agency, 2005). The effectiveness of the introduction of CAMS within river catchment areas is still yet to be fully assessed.

However, some workers remain sceptical that low flow conditions within rivers can be attributed to over-abstraction (Agnew *et al*., 2000; Clayton *et al*., 2008). Within their study Agnew *et al*. (2000) suggested that two chalk streams in Hertfordshire continued to experience low flow conditions despite a decrease in abstraction activities by water companies. They suggested that determining low flow impacts in these rivers was difficult due to the short term nature of hydrological datasets (<25 year) for each river in addition to the long term history of water exploitation within both waterbodies (Agnew *et al*., 2000).

Indications of increased fine sediment supply within stream and river channels include increased turbidity (Jarvie *et al*., 2006; Sanders *et al*., 2007; Walling and Amos, 1999; Wheater *et al*., 2007) and colmation (Heppell *et al*., 2009; Schälchli, 1992; Wood and Armitage, 1999) as well as decreases in ground-water to surface-water exchange (Collins and Walling, 2007c; Heppell *et al*., 2009; Packman and MacKay, 2003). Increased fine sediment retention and storage within gravels can lead to smothering of fish ova (Cordone and Kelley, 1961; McKim *et al*., 1974), the ova of salmonid species like the brown trout (*Salmo trutta* L.) are particularly vulnerable to smothering by fine sediment (Acornley and Sear, 1999). Increased suspended sediment can impare the health and mobility of juvenile and adult fish (McKim *et al*., 1974; Ritchie, 1972). Additionally, fine sediment can impact macrophyte abundance due to the combined effects of reduced light penetration (Walling *et al*., 2006), smothering (Walling and Amos, 1999; Walling *et al*., 2006; Wood and Armitage, 1997) and physical abrasion (Biggs, 1996). Increases in fine sediment concentrations have also been shown to reduce invertebrate mobility against flow (Wood and Armitage, 1997) and increase invertebrate drift (Ciborowski *et al*., 1977; Wood and Armitage, 1997). In summary, fine sediment not only impacts the physical environment of streams and rivers, but has detrimental effects on the survival and life cycles of the organisms that live within them.

Fine sediment has also been linked to the transport, storage and cycling of contaminant elements and compounds within rivers and streams (Droppo and Leppard, 2004; Palmer-Felgate *et al*., 2010; Walling *et al*., 2006). Sediments with high silt and clay (0.06-63 µm) content have been identified as important for contaminant transport and retention due to the relatively large particle surface area and their geochemical composition (Stone and Droppo, 1994; Wood and Armitage, 1997). Contaminants that are commonly linked with fine sediment include man-made compounds such as disinfectants and their associated by-products (Kümmerer, 2001; Mattei *et al*., 2006), as well as naturally occurring inorganic and organic substances (Jarvie *et al*., 2006; Jarvie *et al*., 2008). Previous studies have revealed that petroleum hydrocarbons (Archaimbault *et al*., 2010; Fleeger *et al*., 2003; Walling *et al*., 2003), heavy metals (Archaimbault *et al*., 2010; Droppo and Leppard, 2004; Fleeger *et al*., 2003; Owens *et al*., 2005; Walling *et al*., 2003), pesticides (Archaimbault *et al*., 2010; Faggiano *et al*., 2010; Fleeger *et al*., 2003; Liess and von der Ohe, 2005; Ricart *et al*., 2010) and herbicides (Fleeger *et al*., 2003; Kosinski, 1984; Mullison, 1970) bound to fine sediment particles have a direct detrimental impact on aquatic flora and fauna.

Much attention has recently been paid to the impact of pollutants on river systems from point sources and diffuse sources. A key driver for research into surface and groundwater pollutants within the UK and European Union (EU) has been the implementation of the Water Framework Directive (WFD 2000/60/EC) (Bowes *et al*., 2010; EC, 2000; Mainstone and Parr, 2002). One of the many goals of the WFD is a reduction in sediment-associated pollution within freshwater habitats (Förstner, 2003).

Both nitrogen as nitrate (NO_3^-) and phosphorus as phosphate (PO_4^{3-}) are common sediment-bound compounds that are cycled and processed within rivers and streams at low concentrations. But within many lowland streams nitrate and phosphate are present in higher concentrations due to increased inputs of fine sediment (Bowes *et al*., 2005; Bowes *et al*., 2010; Mainstone and Parr, 2002; Watson, 2007). The oversupply of nitrate and phosphate from riparian agricultural pastures has been suggested as a possible cause of river habitat deterioration (Jarvie *et al*., 2006; Palmer-Felgate *et al*., 2010; Withers and Jarvie, 2008) and river eutrophication (Neal *et al*., 2010; O'Hare *et al*., 2010).

In recent years there has been much concern regarding the ecological health of chalk streams in the UK, and in particular their sensitivity to oversupplies of fine sediment. Chalk streams are known for their high biodiversity and productivity (Bowes *et al*., 2005; Bradford, 2002; Mainstone and Parr, 2002), crystal-clear water (Sear *et al*., 1999; Walling and Amos, 1999) and generally stable flow, chemical and temperature regimes (Berrie, 1992; Dawson, 1976; Sear *et al*., 1999; Walling *et al*., 2006; Wharton *et al*., 2006). They are groundwater-fed lowland streams and rivers that originate from or have most of their channel course flowing over chalk geology (Berrie, 1992; Mainstone, 1999). The chalk stream habitat possesses high-priority conservational species such as the water vole (*Arvicola terrestris* L.), otter (*Lutra lutra* L.), brown trout (*Salmo trutta* L.), Atlantic salmon (*Salmo salar* L.), lampreys (*Lampetra planeri* Bloch and *Petromyzon marinus* L.) and endemic benthic invertebrates such as the white clawed crayfish *Austropotamobius pallipes* (*Lereboullet*) (Acornley and Sear, 1999; Collins and Walling, 2007a; Smith *et al*., 2003). Some of the above species are renowned for being highly sensitive to fine sediment and anthropogenic-associated perturbations (Berrie, 1992; Butcher, 1933; Park, 1981; Walling *et al*., 2006).

The sensitivity of chalk stream habitats has resulted in them being designated a UK Biodiversity Action Plan (UKBAP) habitat (Sanders *et al*., 2007; UKBAP, 2000), which provides environmental legislative protection for these habitats and their associated species. Additionally, most chalk streams are located within designated Sites of Special Scientific Interest (SSSI's) (Mainstone, 1999). Chalk streams are also well known for their *Ranunculus*-dominated aquatic macrophyte communities (Haslam, 1987; Marshall and Westlake, 1990) which provide important ecological functions for other associated species (Gregg and Rose, 1985; Mainstone and Parr, 2002). These communities and guilds of species are sensitive to excessive supplies of fine sediment (Hatton-Ellis and Grieve, 2003).

Previous studies have highlighted a few cases where chalk stream habitats have deteriorated over the last decade (Environment Agency, 2001; Heywood and Walling, 2003; Jarvie *et al*., 2006), with only 37 % of the total number of chalk streams being classed as 'very good' in terms of biological and chemical quality (Environment Agency, 2004; UKBAP, 2000; Walling *et al*., 2006). The term 'chalk stream malaise' describes the general deterioration of the chalk stream habitat, which is caused in part by excessive inputs of fine sediment (DEFRA, 2003; Environment Agency, 2001; Environment Agency, 2004; Heywood and Walling, 2003; Jarvie *et al*., 2006; Mainstone, 1999; Mainstone *et al*., 2008; Walling *et al*., 2006; Wheater *et al*., 2007). Symptoms include a decrease in the abundance of macrophytes, fly species, brown trout and salmon within some chalk rivers (Heywood and Walling, 2003; Mainstone *et al*., 2008). Furthermore, excessive sedimentation has been determined as a major water quality problem in the upper reaches of the southern chalk streams including the Rivers Frome, Piddle, Test, Itchen and Kennet (Environment Agency, 2004; Environment Agency, 2005).

In summary, it is clear that the oversupply of fine sediment has a detrimental effect on the water quality, ecology and geomorphology of lowland streams like the UK chalk streams. Previous studies have focused on quantifying the input, deposition and retention of fine sediment within UK chalk streams. In contrast, there has been very little analysis of the transport element of the fine sediment transport cycle within UK chalk streams, and more generally lowland gravel-bed streams. Additionally, the role of aquatic macrophytes within the fine sediment transport cycle of all streams and rivers is still not fully understood.

The purpose of this research was to further investigate what roles aquatic macrophytes have within the fine sediment cycle of lowland gravel-bed rivers, focusing primarily on chalk streams. What follows in Chapter 2 is a comprehensive literature review that focuses further on fine sediment and the fine sediment transport cycle, our current understanding of sediment-aquatic macrophyte relationships within rivers and previous investigations to estimate fine sediment transport within rivers. This ends with a summary of the knowledge gaps in the literature and a statement of the research aims and specific questions.

CHAPTER 2

Literature review

2.0 Introduction

This review compares and contrasts previous studies and recent developments relating to fine sediment transport and retention within rivers and streams, with an emphasis on studies related to vegetated streams and rivers. Section 2.1 will define what fine sediment is, and discuss some of its important characteristics. Sections 2.2 to 2.4 inclusive discuss the main components of the sediment transport cycle within lowland streams and rivers. Section 2.4 provides a description of how fine sediment transport is estimated within streams and small rivers, with particular focus on fine sediment transport within vegetated rivers and streams. This is followed by section 2.5 which is a review of the previous work relating to fine sediment retention and storage within rivers and streams and the role of aquatic macrophytes. The chapter ends with a summary that describes the current gaps in knowledge in section 2.6, and a statement of the research aims and specific questions for this study in section 2.7.

2.1 What is fine sediment?

Sediment is defined by Soanes and Stevenson (2004) as "1. matter that settles to the bottom of a liquid, and 2. particulate matter that is carried by water or wind and deposited on the surface of the land or the bottom of a body of water"[1]. This statement is open to much interpretation and has led to some potentially heated deliberation over what constitutes sediment and fine sediment in particular. Previously, sediment has been characterised qualitatively as well as quantitatively by its physical (Ongley and Bynoe, 1982; Phillips and Walling, 1995; Walling and Moorehead, 1989; Wentworth, 1922), chemical (Evans *et al*., 2004; Ongley and Bynoe, 1982) and biological properties (Triska *et al*., 1989; Wotton, 1996; Wotton and Malmqvist, 2001).

[1] Quote taken from page 2795 Soanes, C. and Stevenson, A., 2004. The concise Oxford English Dictionary. Oxford University Press, New York.

The physical, chemical and biological properties of river sediments depend on the variability of the climate, local hydrological and geomorphological conditions within the channel, as well as the nature of the sediment erosion and delivery to the channel (Harvey *et al*., 2008; Jones *et al*., 2011). Fine sediment can originate from a non-channel (allochthonous) or within-channel source (autochthonous) (Wood and Armitage, 1997). *In-situ* river processes like the interception, ingestion and breakdown of large particles by invertebrates, as well as aggregation of ultra-fine particles (Wotton, 1984) will determine the eventual structure of fine sediment. Fine sediment can exist in many different physical forms ranging from the most stable and cohesive clay beds to the most fragile 'fluffy' flocculated form (e.g. Droppo, 1991).

Fine sediment is a natural component of rivers and streams. It is a heterogeneous matrix of inorganic or organic particles. Inorganic particles within fine sediment are mineral particles of sand (63-2000 μm), silt (2-63 μm) and clay (<2 μm). Organic particles or fine particulate organic matter (FPOM) comprise spores, pollen grains, microbes, extracellular polymer substances (EPS) (Droppo, 2001), invertebrate carcasses, woody debris, plant fragments and seeds (Riis and Sand-Jensen, 2006) as well as faecal pellets (Ladle and Griffiths, 1980; Wotton *et al*., 1998). Earlier work on fine sediment involved the complete removal of the organic components leaving only the inorganic particles for analyses (Einstein, 1950; Hjulström, 1939). Contemporary studies on fine sediment have analysed both organic and inorganic particles within sediment by classifying sediment fractions as either effective and absolute (Heppell *et al*., 2009; Walling and Amos, 1999; Wharton *et al*., 2006). The effective or *in-situ* component of fine sediment consists of both organic and mineral particles (Phillips and Walling, 1995; Walling and Amos, 1999), and the absolute fraction contains only chemically dispersed inorganic particles with all organic elements removed (Phillips and Walling, 1995). The organic component of fine sediment can sometimes be considerable, and organic particles are often very different to inorganic particles in terms of particle size, shape and density.

A further common classification of fine sediment uses particle size distribution (Golterman, 1983), as the particle size of fine sediment has direct and indirect influences on its transport and geochemical dynamics (Hjulström, 1939; Phillips and Walling, 1995). Previously, there was debate over whether fine sediment or 'fines' was just the silts and clays (<63 μm) (Collins and Walling, 2007c), or whether it also included sand fractions. Current workers generally define fine sediment or fines within streams and rivers as less than gravel (<2 mm) in respect to particle size (Heppell *et al*., 2009; Jones *et al*., 2011; Owens *et al*., 2005; Wharton *et al*., 2006; Wood and Armitage, 1997; Wood and Armitage, 1999). The standard definition of fine sediment used within physical geography and earth sciences is usually equivalent to the Wentworth Scale (Wentworth, 1922) where the particle size lies between the very coarse sand (2000 μm) and very fine clays (0.06 μm).

Within biological sciences there has been a tendency to focus on FPOM within rivers to analyse biological food webs, nutrient cycles and spiralling (Malmqvist *et al*., 2001; Newbold *et al*., 1981; Wood and Armitage, 1997; Wotton *et al*., 1998) or the transport of invertebrates and fine sediment particles within streams and rivers (Broekhuizen and Quinn, 1998; Cushing *et al*., 1993; Ehrman and Lamberti, 1992; Georgian *et al*., 2003; Minshall *et al*., 2000; Newbold *et al*., 2005; Warren *et al*., 2009; Webster *et al*., 1987). Within those studies FPOM is defined as particles with diameters <1000 μm (Cushing *et al*., 1993; Vannote *et al*., 1980; Webster *et al*., 1999; Webster *et al*., 1987) essentially removing the 1000-2000 μm (very coarse sand) fraction recognised by the Wentworth scale (Wentworth, 1922).

Within this study fine sediment particles are considered to be a mixture of aggregated and disaggregated mineral and organic particles. The particle size distribution of fine sediment is considered to be between the lower limit of the clay (0.06 μm) and coarse sand (1000 μm) so that fine sediment fractions can be compared directly with previous studies on FPOM. This approach is consistent with other interdisciplinary studies on fine sediment within rivers and streams (Cotton *et al*., 2006; McConnachie and Petticrew, 2006; Sidle, 1988; Welton, 1980).

What follows is a further description of the transport and deposition of fine sediment particles within rivers.

2.2 Fine sediment transport and deposition within rivers

The transport of fine particulate sediment is a central component of the longitudinal linkage of the river continuum concept (Vannote *et al*., 1980) which includes the transport and cycling of FPOM in the nutrient spiralling concept (Newbold *et al*., 1981). It is understood that fine sediment can be transported and exchanged between the groundwater, the hyporheic zone and the surface water (Heppell *et al*., 2009; Lambert and Walling, 1988).

This remainder of this review focuses on fine sediment transport within the surface water of rivers and streams which can be divided into three main stages: (1) provenance; (2) transport downstream; (3) deposition and storage. At the end of this chapter is a summary of the current gaps in knowledge.

2.3 The provenance of fine sediment

The entry of fine sediment into a stream or river course can be described as either allochthonous or autochthonous.

Allochthonous additions of fine sediment within lowland stream catchments have mostly been traced to anthropogenic disturbances (Wood and Armitage, 1997). The main sources of fine sediment supplied into rivers are exposed soils, mass failures within the catchment, drainage from urban areas, anthropogenic activities, litter from riparian vegetation (e.g. leaf litter) and from the atmosphere (Wood and Armitage, 1997). Routeways or transient pathways for fine sediment into rivers include aeolian processes and precipitation as well as drainage from small tributaries, dykes, drains, farm tracks and roads (German and Sear, 2003).

Currently, the determination of the origin and routeways of fine sediment into streams and rivers relies on either direct observation during heavy storm periods or 'fingerprinting' (Walling and Amos, 1999). Fingerprinting matches the physical and chemical composition of suspended sediment particles with potential sediment sources (Walling and Amos, 1999). These potential sediment sources are usually areas where there has been a change in land-use, and in particular, a change in agricultural practices. Surface sediment from cultivated and pasture fields were found to be the greatest source of fine sediment in comparison with sediment eroded from the banks within the Pang-Lambourn catchment (Collins and Walling, 2007c; Walling *et al*., 2006), upper Piddle catchment (Walling and Amos, 1999) as well as the Rivers Tern (Collins and Walling, 2007c) and Wylye (German and Sear, 2003).

Autochthonous sources of fine sediment include erosion of channel banks, surficial and stored fine sediment within the bed, the resuspension of fine sediment from macrophyte beds, and additions of biotic particles (Wood and Armitage, 1997). Within vegetated lowland streams and chalk streams in particular, a large proportion of fine sediment originates from stored fine sediment within gravel beds (Collins and Walling, 2007a; Collins and Walling, 2007c) and macrophyte beds (Cotton *et al*., 2006; Heppell *et al*., 2009; Wharton *et al*., 2006).

After fine sediment has entered the stream it is generally transported by stream flow in the downstream direction (Vannote *et al*., 1980). The distance in which a single particle of sediment travels downstream is dependent on a number of factors.

2.4 The transport of fine sediment within streams and rivers

When a sediment particle enters the stream flow there are a number of conditions and thresholds that need to be met in order to begin transport. A grain of fine sediment is transported after a critical or threshold level of energy has been achieved for entrainment. The initiation of sediment particle mobility is dependant on a number of hydro-geomorphological conditions such as slope, discharge, water column depth, critical velocity, drag and lift forces, shear velocity, (Hjulström, 1939) shear stress (Mesri *et al*., 1981) as well as the position of individual particles within the water column and cross-section of the channel (Gordon *et al*., 2004). The physical properties of sediment particles are also important in transport processes. These include particle diameter, particle density, particle shape, and particle depositional velocity (Golterman, 1983; Gordon *et al*., 2004).

The study by Hjulström (1939) identified that a specific threshold of critical velocity was required in order to move unconsolidated mineral sediment particles ranging from fine clays to gravel (Figure 2.1). The mean velocities required for entraining and transporting individual particles of silts and clays were found to be considerably greater in comparison to sand and greater sized particles (>63 µm). Furthermore, a larger amount of energy is required to entrain a particle than to maintain its transport downstream. The inherent problem with the Hjulström curve is that it is based on singular mineral particles only, and it does not consider particle density which is also an important factor. Organic particles generally have lower values of bulk density in comparison with mineral particles of the same particle size (Rowell, 1994). It was estimated that organic particles with a bulk density of 1.050 kg/m^3 only required

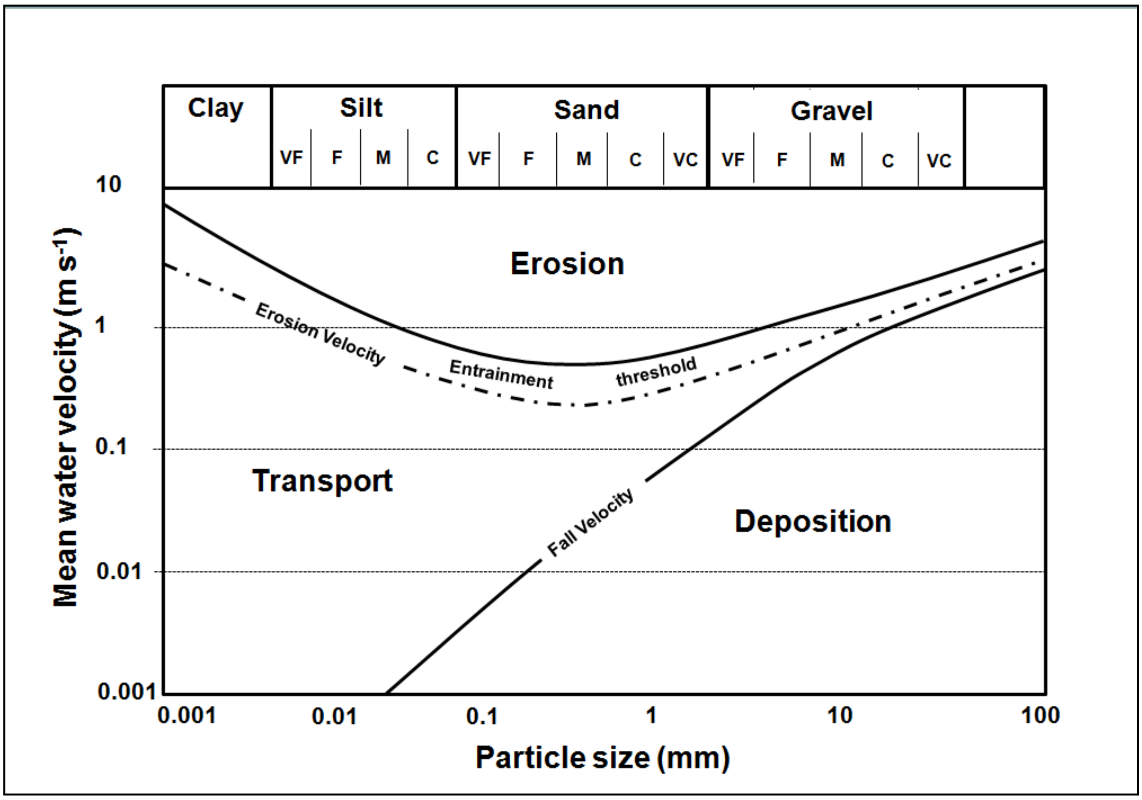


Figure 2.1 – The Hjulström curve redrawn from Hjulström (1939) illustrating the mean velocity thresholds required for transport, erosion and deposition of mineral particles from clay to cobble-size (0.001-100 mm). Descriptions of particle size are taken from the Wentworth Scale (Wentworth, 1922).

1/6 of the critical velocity that was necessary to initiate the motion of comparative mineral particles (Smith, 1975). Fine sediment found within river and streams is commonly a mix of organic and mineral particles that can be present in aggregated and disaggregated forms of varying consistencies. These two factors can be problematic when attempting to estimate fine sediment transport and deposition within rivers.

In previous estimates of fine sediment transport there are two generalised fates for particles when they enter the water column. They are either suspended within the flow and are therefore assumed to be part of the percentage that is transported, or they fall out of suspension to the benthos and are considered deposited or part of the percentage that is lost. This oversimplifies the complex processes and interactions of the sediment transport cycle within streams and rivers. Since most fine sediment within streams and rivers is in constant suspension or within a constant state of flux between being transported and deposited, spanning from the uppermost surface of the water column to the stream bed (Cushing *et al*., 1993).

Sediment can classified into three main types of load, these are the floatation load, the dissolved load, and the sediment load. The flotation load comprises coarse objects that float on the surface waters such as woody debris, leaves and other organic and inorganic debris. The dissolved load consists of the material that is transported within solution. These include dissolved salts from the surrounding geology in the catchment in addition to any organic and inorganic chemicals and compounds that drain into the channel from the land (Gordon *et al*., 2004). The final category is the sediment load, which can be further separated into three layers from the waters' surface down to the bed substratum. These include in ascending order the wash load, the suspended load and the bedload.

In reference to the Wentworth Scale (Wentworth, 1922) the washload is composed of suspended small sediment particles from primary clay particles to the beginning of sand grade particles (0.5-62 μm) (Gordon *et al*., 2004). Minor amounts of turbulence and velocity are required to keep these particles in suspension (Hjulström, 1939).

Sediment particles that are entrained and remain suspended within water flow for extended time periods are referred to as the suspended sediment load (Gordon *et al*., 2004). Previous studies have attempted to characterise the suspended sediment within lowland rivers and streams. Analyses on the headwater the River Piddle determined that the suspended sediment was composed of <5 % sand (2000-63μm), 65 % silt (2-63 μm) and 30 % clay (<2 μm) (Walling and Amos, 1999). These results were similar to a study on another chalk river called the River Test by Acornley and Sear (1999), who determined that fine suspended sediment was composed mostly of silt (4-63 μm) with a considerable fine sand fraction (63-250 μm) at high discharges. There are a number of factors that govern the composition and variability of suspended sediment characteristics. These include temporal variability (Walling and Moorehead, 1989), the location of the river catchment (Vannote *et al*., 1980), the underlying geology (Harvey *et al*., 2008), local agricultural practices and other anthropogenic impacts (Brookes, 1986), catchment and riparian vegetation type (Corenblit *et al*., 2007) and many cyclical and non-cyclical hydro-geomorphological and biological processes occurring *in-situ* (Phillips and Walling, 1995).

Fine sediment particles that cannot be entrained far enough into the water column and fall subsequently after entrainment are referred to as the bedload. Particles that form the bedload are not static, and it has been suggested that particles of fine sediment often fail to settle after they contact the channel bed for the first time (McNair and Newbold, 2001). Instead they are transported by saltating, rolling and sliding along the bottom of stream and river beds (Gordon *et al*., 2004; Hjulström, 1939). Their progress downstream as bedload is much more limited or slower in comparison to suspended particles (Gordon *et al*., 2004; Hunken, 2006; Wilcock, 1997). It is possible that fine sediment forming the bedload is often analysed as deposited fine sediment due to its slower transit time through a system in comparison to suspended fine sediment.

Sediment load moving within a river channel can be characterised using Rouse numbers, devised by Henry Rouse to describe the method by which sediment is being transported within a river channel. The dimensionless Rouse numbers are produced by the Rouse equation:

$$P = \frac{W}{\kappa u_*} \qquad [1]$$

where w is the settling velocity, κ is Von Karman's constant, and u_* is the shear velocity. When Rouse values are ≥2.5 sediment loads are transported by bedload. Values between 2.5 and 0.8 indicate that sediment is in incipient suspension and values of <0.8 indicate sediment being totally suspended with no contact to the bed substratum (Julien, 1998).

Estimates of fine sediment transport within rivers and streams have often relied on both field and laboratory methods. Some of the most recent methods employed will be discussed and their results compared in the following section.

2.4.1 Previous methods of estimating sediment transport characteristics within rivers and streams

A number of methods have been used to provide estimates of fine and coarse sediment transport within streams and rivers. However, sediment transport investigations usually fall into two distinct categories. The first is sediment rating where a sediment rating curve is used to observe the fluvial transport sediment and fluxes over time using continuous data for discharge and sediment concentration. The second is space-time routing which uses models to estimate the transport of sediment through a system or channel using known or generalised parameters. The following review is centred upon space-time routing techniques used in flumes, experimental channels and natural channels.

Space-time routing of sediment within rivers is scale-dependent, for example the particle-scale (*cf.* fingerprinting Collins *et al*. (1997), Walling and Amos (1999)), reach-scale (Miller and Georgian, 1992), river-scale (Newbold *et al*., 2005) or catchment scale (Walling and Amos, 1999). Many studies have employed sediment transport models based on data from previous empirical or theoretical work (e.g. Einstein (Einstein, 1950)), in comparison with other studies that have employed experimental and laboratory flumes to control hydrological and geomorphological parameters (Engelund and Fredsoe, 1976).

Recent studies have produced more realistic estimates of transport using analogue or labelled natural sediment particles (Miller and Georgian, 1992). Examples of the latter have been used within laboratory flumes (Warren, 2006; Warren *et al*., 2009), experimental field channels (Paul and Hall, 2002; Thomas *et al*., 2001; Webster *et al*., 1987), as well as natural river channels (Cushing *et al*., 1993; Georgian *et al*., 2003; Miller and Georgian, 1992; Minshall *et al*., 2000; Thomas *et al*., 2001; Warren *et al*., 2009). The rest of this section will focus on sediment transport estimates using analogue and labelled particles natural streams and rivers, except where examples are given of sediment transport studies undertaken within experimental flume studies.

A range of empirical studies have used labelled analogue and natural particles to estimate the transport and drift of invertebrates, as well as coarse to fine particulate sediment within streams and rivers. The earliest transport experiments within rivers and streams involved conspicuous analogues to estimate the mean transport distance (S_P, m) of invertebrate drift downstream (Elliott, 1971; McLay, 1970). These early studies provided the basis for estimating the transport and retention of coarse particulate organic matter (CPOM) in the form of riparian leaves within rivers and streams using painted leaves (Young *et al*., 1978), ginkgo leaves (Speaker *et al*., 1984) and plastic strips (Speaker *et al*., 1988).

The first fine particulate sediment transport experiments within natural stream channels were implemented by Maciolek & Tunzi (1968), who determined that bleached *Asterionella* and *Stephanodiscus* cells (15-80 μm) were transported in a mountain stream in excess of 4000 m by stream flow alone, and only 450 m when Simuliidae larvae were present. Other workers have also used biological particles as fine sediment analogues to estimate S_P (Table 2.1). Although these studies have contributed greatly to our current knowledge of fine particle transport in streams and rivers, they are not directly comparable to one another for several reasons.

Table 2.1 - Previous sediment transport experiments of other workers have used a variety of analogue particles, with corn pollen frequently used by a number of workers . The distance of sediment transport was estimated in the majority of experiments but not all. Experiments were conducted within streams that are different in terms of stream order, channel morphology, catchment type, flow characteristics and discharge.

Date	Author(s)	Country	Stream/river type	Catchment habitat	Particles used	Particle diameters (µm)	Transport distance (m)
1963	Maciolek & Tunzi	USA	2nd order stream	Mountain	Diatoms cells	15-80	~4000
1978	Young et al.	USA	3rd order stream	Woodland	Red oak, beech and red maple leaves	not given	106-557
1981	Dawson	UK	1st order stream	Lowland woodland & pasture	Fine sediment	0.8-2000	Not estimated
1984	Speaker *et al.*	USA	3rd & 4th order streams	Forest	Gingko leaves	not given	15-210
1987	Webster *et al.*	USA	Artificial stream channels	n/a	Seived sediment particles	102-240	11.2
1987	Webster *et al.*	USA	Artificial stream channels	n/a	Seived sediment particles	240-560	9.7
1987	Webster *et al.*	USA	Artificial stream channels	n/a	Seived sediment particles	>560	9.3
1987	Webster *et al.*	USA	2nd order stream	n/a	Painted leaves	100-1000	0.5-7
1988	Speaker *et al.*	USA	3rd & 4th order streams	Forest	Gingko leaves	not given	>660
1991	Jones & Smock	USA	3rd order stream	n/a	Radio-labelled sediment particles	50-100	2-84
1992	Ehrman & Lamberti	USA	3rd order stream	Woodland	Gingko leaves	not given	109-168
1992	Miller & Georgian	USA	2nd order stream	Woodland/Scrub	Corn pollen	87-89	122-190
1993	Cushing *et al.*	USA	2nd order stream	Forest	C^{14} labelled sediment particles	53-102	580-800
1994	Cushing *et al.*	USA	3rd order stream	Forest	C^{14} labelled sediment particles	53-103	<580
1996	Hall *et al.*	USA	2rd order stream	Mountain	Fluorescent-labelled bacteria	2	~80
1998	Broekhuizen *et al.*	New Zealand	1st & 2nd order streams	Lowland pasture and forest	Corn pollen	87-89	34-294
1999	Bonniwell *et al.*	USA	Large order river	Forestry	Fall-out radionuclide-labelled particles	2-6	15000-60000
2000	Minshall et al.	USA	1st, 2nd & 3rd order streams	Mountain	C^{14} labelled sediment particles	53-106	6.7-1000
2001	Wanner & Pusch	Germany	6th order river	Lowland valley	Fluorenscent-labelled *Lycopodium* spores	33	Not estimated
2001	Thomas *et al.*	USA	1st & 2nd order streams	Mountain	C^{14} labelled sediment particles & diatoms	15-250	4.4-308
2002	Pall & Hall	USA	1st-5th order streams	Forest	Fluorenscent-labelled brewers yeast	5-7	4-409
2003	Georgian *et al.*	USA	1st, 2nd & 3rd order streams	Mountain	Corn pollen	87-89	183-687
2003	Georgian *et al.*	USA	1st, 2nd & 3rd order streams	Mountain	C^{14} labelled sediment particles	53-106	235-1164
2005	Newbold *et al.*	USA	2nd order stream	Mountain	C^{14} labelled sediment particles	15-106	510-750
2007	Hunken & Mutz	Germany	Lowland streams	Lowland rural and ex-mining	Slug of natural organic particles	0.45-53	21-556
2009	Warren *et al.*	UK	1st order stream	Lowland agricultural pasture	Corn pollen	87-89	63-91

Firstly, the field methodologies used to estimate S_P differ between studies (Miller and Georgian, 1992) . Secondly, each study used different tracer particles or fine sediment analogues. Thirdly, the streams in Table 2.1 that used for experimental work generally differed in terms of stream order and slope as well as geomorphological features such as the bed substratum. Lastly, only a few studies included estimates of the number or concentration of particles in transport at different stations along the river or stream course *c.f.* Miller and Georgian (1992) and Hunken and Mutz (2007).

It is clear that an uncomplicated standardised method should be used to analyse fine particle transport so that results of releases within different streams and rivers can be directly compared. An improved method for estimating FPOM transport was proposed by Miller and Georgian (1992). Their work suggested the use of corn pollen as analogue FPOM particles, and included an estimate of the number of corn pollen particles in transport, in addition to estimates of S_P. A further benefit is that the resulting data can be used to calculate other hydrological parameters such as the depositional velocity (V_{dep}, mm s^{-1}), which is useful for comparing release data between streams and rivers with different channel dimensions (Cushing *et al*., 1993). Other beneficial considerations are the relatively inexpensive cost of the experiments since there are no requirements for specialised equipment or the use of radio-nucleotides labels, and any results can be obtained simply by scanning filtered sediment under a dissection microscope (Miller and Georgian, 1992). Additionally, corn pollen can be dyed to make it conspicuous against the background fine sediment matrices within samples (Miller and Georgian, 1992; Warren *et al*., 2009; Zangerl *et al*., 2001). This methodology has been adapted for use in a number of studies within North America (Georgian *et al*., 2003; Webster *et al*., 1999), one study in England (Warren *et al*., 2009) and one in New Zealand (Broekhuizen and Quinn, 1998).

An analysis comparing the transport properties of corn pollen and natural fine particulate sediment (53-1000 μm) within the same stream was performed by Georgian *et al*. (2003). Their work concluded that under the same hydrological and geomorphological conditions both particles showed comparable transport distances. The ratio of corn pollen: FPOM S_P from their analyses ranged from 0.55 to 1.10. This led to them to suggest that corn pollen was a highly suitable analogue particle to estimate the transport of 'natural' fine particulate sediment (50-100 μm), which included aggregates of organic and inorganic particles.

In addition to S_P, there are several other parameters that can be used to analyse sediment transport and retention within streams and rivers.

2.4.2 Particle longitudinal loss rate (K_P) as a sediment transport and retention parameter

K_P (m^{-1}) is a parameter that was originally described in the work by Webster *et al.* (1987) who referred to this as the 'uptake rate' or K_L. It has also been used subsequently after by other workers in similar studies (Broekhuizen and Quinn, 1998; Cushing *et al.*, 1993; Hall *et al.*, 1996; Miller and Georgian, 1992). This parameter represents the instantaneous rate of particle loss per metre of a stream (Miller and Georgian, 1992).

K_P is greatly influenced by the hydrological and geomorphological characteristics of the channel. The releases by Minshall *et al.* (2000) suggested that values of K_P were significantly higher in the mountain stream with the least values of mean water depth (h), mean water flow velocity (u) and Q, with the greatest reported K_P value reported as 0.171 m^{-1}. Work presented by Georgian *et al.* (2003) from releases of corn pollen and natural FPOM in their mountain streams also indicated that low values of Q, u and h led to higher values of K_P. The highest K_P values obtained for corn pollen and natural FPOM were 0.0045 and 0.0043 m^{-1} respectively (Georgian *et al.*, 2003).

There have also been studies that have compared variations in K_P with sediment particle size. The analysis by Thomas *et al.* (2001) suggested that there were only comparatively small differences between the K_P values for FPOM (54-106 μm) and VFPOM (15-53 μm), which were between 0.232-0.002 m^{-1} and 0.227-0.001 m^{-1} respectively. However, this is a greater range of variability compared with the K_P values from experimental releases of by Hunken and Mutz (2007), who found K_P varied between 0.048 and 0.005 m^{-1} for sediment slugs of combined VFPOM and UFPOM (0.45-53 μm). The comparison of the findings of these two studies further illustrate the disadvantages of using particles of variable size to compare fine sediment transport and retention between different streams.

Nevertheless, the longitudinal loss rate is a good estimate for the rate at which particles leave transport in suspension to be deposited and retained. The potential problem with K_P estimates is that they are influenced by factors relating to the geomorphology and hydrology of the experimental stream or river, *e.g.* mean water depth and mean water flow velocities. Also, it is apparent that K_P values relate specifically to particle size. Due to the variation in these factors, it is difficult to compare particle transport and retention between different streams and rivers using values of K_P.

2.4.3 V_{dep} as a sediment transport and retention parameter

Values of V_{dep} are mass-transfer coefficient values or values of downward velocity at which particles travel from a fully-mixed water column to the stream bed (Cushing *et al*., 1993; Dobbins, 1944; Smith, 1982). The calculation of V_{dep} removes the influence of stream size (depth and velocity) from K_P, which enables a direct comparison of particle transport distances and retention between streams independent of differences in size and discharge (Cushing *et al*., 1993; Georgian *et al*., 2003).

The results presented by Georgian *et al*. (2003) indicated that V_{dep} values for corn pollen were similar to those of natural FPOM within their study stream. They also demonstrated that V_{dep} values appeared to be higher in streams with the lowest values of mean depth and mean water velocity. This concurred with the findings of the study by Minshall *et al*. (2000), who found that V_{dep} values in two of their smaller streams were 3-4 times greater (0.87-0.83 mm s^{-1}) than those of the larger streams in their study (0.28-0.06 mm s^{-1}). A primary conclusion from the work of Minshall *et al*. (2000), Thomas *et al*. (2001) and Hunken and Mutz (2007) was that the main drivers of fine particle deposition within natural stream channels are still unclear. But these drivers are possibly influenced by a combination of synergistic and antagonistic factors (Hunken and Mutz, 2007). The influence of particle settling velocity and gravitational velocity on V_{dep} have been analysed by previous workers in greater detail.

The influence of particle settling velocity or terminal velocity in quiescent water (V_{fall}, mm s^{-1}) on V_{dep} has been discussed by a number of workers (Cushing *et al*., 1993; Georgian *et al*., 2003; Hall *et al*., 1996; Hunken and Mutz, 2007; Minshall *et al*., 2000; Thomas *et al*., 2001). Values of V_{fall} describe the gravitational settling of particles in a laminar sublayer without resuspension (Dobbins, 1944; Thomas *et al*., 2001). This differs to V_{dep} which is a representation of hypothetical particle settling within a turbulently mixed water column (Dobbins, 1944; Thomas *et al*., 2001). Within traditional gravitational/hydrodynamic models it was predicted that V_{dep} and V_{fall} are equal under simple conditions of a mixed water column with a well-developed laminar sublayer above sediments (Dobbins, 1944; Minshall *et al*., 2000; Smith, 1982). But in the experimental releases by Minshall *et al*. (2000) and Georgian *et al*. (2003) there was great variability found in the ratio of FPOM V_{dep} and V_{fall} with values found to be <1. Additionally, a few workers have concluded that V_{dep} of FPOM is 'uncoupled' from V_{fall} (Cushing *et al*., 1993; Hall *et al*., 1996; Thomas *et al*., 2001), and that the probability of particles hitting the stream bed is dependent on vertical mixing rather than passive sinking (McNair and Newbold, 2001). This was further explained by Thomas *et al*. (2001), who suggested that V_{fall} had a consistent influence on V_{dep}, and the magnitude of the effect was small but increased in association with increased particle size from 100 μm (Hunken and Mutz, 2007; Thomas *et al*., 2001). The experimental releases conducted by Georgian *et al*. (2003) with corn pollen as the analogue particle concurred with the findings of Thomas *et al*. (2001) and suggested that factors influencing resuspension of particles of 80-100 μm may overwhelm gravitational settling, as illustrated in Figure 2.2.

In addition to gravitational settling, it has been suggested that the transient storage of a channel may influence values of V_{dep}. A significant association between the V_{dep} of FPOM and the hydraulic radius of the channel (R) was demonstrated in the study by Thomas *et al*. (2001). They determined there was a significant linear relationship between FPOM V_{dep} and the result of the ratio between the cross-sectional area of the transient storage zone (A_S) and the cross-sectional area (A). V_{dep} values were higher with the largest values of A_S/A (Minshall *et al*., 2000; Thomas *et al*., 2001). A further set of experimental releases by Hunken and Mutz (2007) determined that the majority of the transient storage within their low-gradient streams was created by zones of low water flow velocity within stream channels. This led them to conclude that values of transient storage between the mountain and lowland streams were different, with mountain streams possessing smaller values of transient storage.

In summary, studies of particle deposition within river channels have suggested that V_{dep} of analogue and natural particles appear to be dependant on two main factors within lowland streams. Firstly, turbulence and other factors influencing particle resuspension within stream and river channels have more effect on particle disposition than the V_{fall} when sediment particles <100 μm. Secondly, the transient storage associated with V_{dep} is dependant on zones of low flow velocities within lowland streams and rivers with a slight gradient. Aquatic macrophytes are common features within UK lowland streams that have been demonstrated to create localised reductions in flow velocity within channels (Champion and Tanner, 2000; Cotton *et al*., 2006; Green, 2005c; Gregg and Rose, 1982; Marshall and Westlake, 1990; Sand-Jensen, 1998; Wharton *et al*., 2006). Therefore, further experimental field analyses are required to increase our understanding of the interactions between macrophyte patches and their impact on fine sediment V_{dep} values within natural streams and rivers.

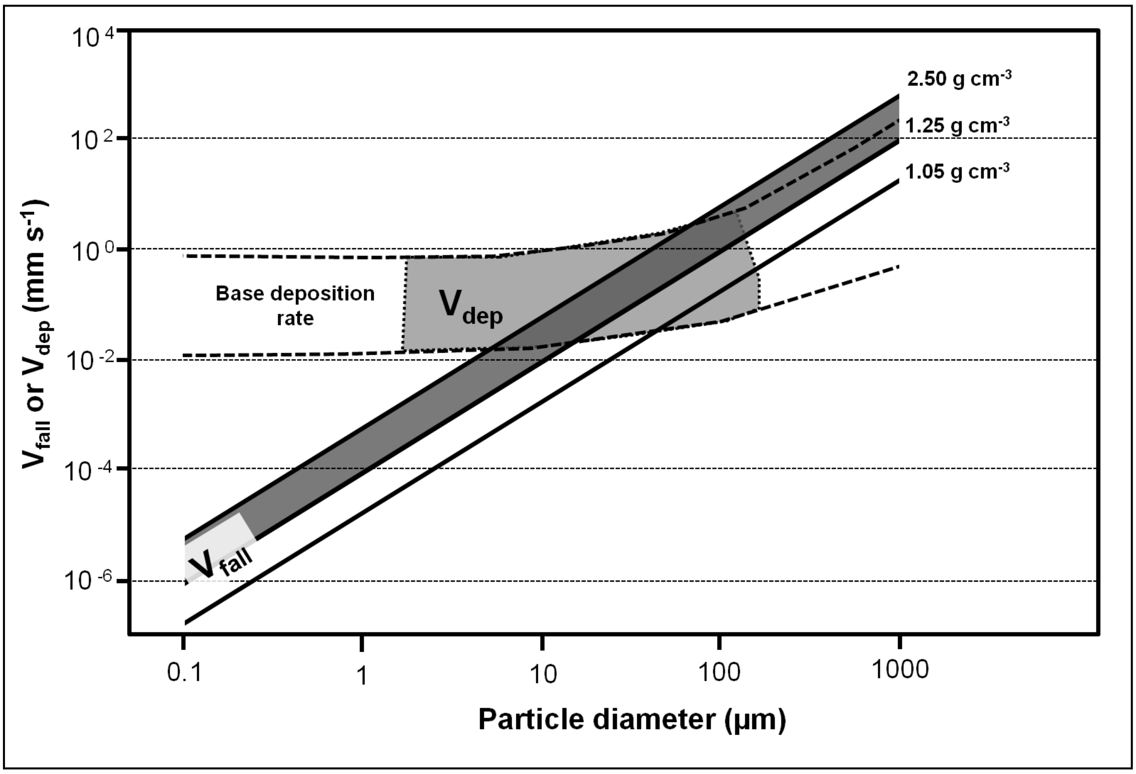


Figure 2.2 – The relationship between fall velocities (V_{fall}) calculated using Stokes Law and the depositional velocity (V_{dep}) trajectory of particles with diameters from 0.1 to 1000 µm redrawn from Thomas *et al*. (2001). V_{fall} values are calculated based on particles with densities of 2.50, 1.25 and 1.05 g cm^{-3}. The values for V_{dep} are based on organic particles from work by Hall *et al*. (1996), Miller and Georgian (1992), Webster *et al*. (1999) and Thomas *et al*. (2001). The lower limit of the base deposition rate is determined by the mass coefficient of water (V_w, m s^{-1}).

2.4.4 Estimates of fine sediment transport involving aquatic macrophytes

There have been many previous studies on sediment transport and retention within rivers and streams. The motivation for the majority of these studies was to investigate geomorphological changes or analyse problematic sediment accumulations (McNair *et al*., 1997).

Work directly investigating the 'engineering' or impact of river macrophytes on fine sediment transport is still scarce. Research has focused on the retention and storage of fine sediment within aquatic macrophyte patches *c.f.* Cotton *et al*. (2006), Heppell *et al*. (2009) and Wharton *et al*. (2006). Thus far there are few examples of previous work that has focused on the seasonal change of macrophytes patches at the reach scale and their role in the fine sediment transport cycle. There are two identified reasons why there is a current lack of related work in this area. Firstly, understanding of the role aquatic macrophytes play in manipulating or engineering the physical habitat of rivers and streams is still developing (Jones *et al*., 2011; Kleeberg *et al*., 2010; Sand-Jensen, 1998; Sand-Jensen and Mebus, 1996; Sand-Jensen and Pedersen, 1999; Sukhodolova *et al*., 2004). Secondly, there are many different submergent and emergent aquatic macrophyte species, each with differing morphologies that affect the hydraulic conditions of the stream they inhabit (Gurnell *et al*., 2010; Haslam, 1987).

Previous field investigations have described the formation of high velocity flow channels within vegetated rivers and streams (Dawson and Robinson, 1984; Gurnell *et al*., 2006; Wharton *et al*., 2006) due to the 'blockage factor' (Green, 2005b; Green, 2005c; Green, 2006) and subsequent constriction of water flow in between dense growths of submerged aquatic macrophytes (Sand-Jensen, 1998). These channels of high flow have been found to be free from fine sediment deposition (Gurnell *et al*., 2006). This has initiated some interest into whether the presence of aquatic macrophytes can increase entrainment and increase sediment transport at the reach scale, as well as encourage deposition of fine sediment within plant patches.

A review of the literature reveals that the quantity of work relating to fine particulate sediment transport within rivers and streams is vast and encompasses many disciplinary areas. Most of the earliest peer-reviewed studies on sediment transport in rivers can be traced back to the mid 20th century (*c.f.* Hjulström, 1939; Dobbins, 1944 and Einstein, 1950). From sixty-six peer-reviewed journal articles primarily focusing solely on fine sediment transport, only six specifically included, mentioned or discussed the possible impacts of aquatic macrophytes on sediment transport. Of those six articles two discussed the modelling of sediment transport in relation to channel macrophytes (Liu and Shen, 2008; Wu and He, 2009), the remaining four were empirical field studies within actual rivers and streams. Of those four studies, two focused on CPOM (>1000 μm) (Horvath, 2004; Koetsier and McArthur, 2000) and the remaining two on FPOM (<1000 μm) (Wanner and Pusch, 2001; Warren *et al*., 2009). Both of the studies focusing on FPOM used natural analogue particles to describe fine sediment transport through vegetated channel sections. Only the study by Warren *et al*. (2009) was specifically designed to investigate the role of macrophytes in fine sediment transport. In comparison, the study by Wanner and Pusch (2001) considered the impact of 'benthic structural elements' on sediment transport and retention. The structural elements within their study included deposited sand on gravel, mussels and reeds as well as submergent aquatic macrophytes.

Further differences between the four studies by Horvath (2004), Koetsier and McArthur (2000), Wanner and Pusch (2001) and Warren *et al*., (2009) included the river or stream order, the dimensions of the study reaches, and the dominant macrophyte species present within each of the experimental rivers. The study by Horvath (2004) used four reaches of a first order stream called the Breitenbach (Germany) that was dominated by *Myosotis palustris* (L.). The investigation by Koetsier and McArthur (2000) used two 100 m sections of first order tributary streams of the Savannah River (NC, USA) populated by *Sparganium americanum* (Nutt.). Wanner and Pusch (2001) conducted their experiments on a regulated sixth order section of the River Spree (Germany) that was dominated by *Sagittaria sagittifolia* (L.). The experimental reach used by Warren *et al*., (2009) was a first order lowland stream in the Piddle catchment (England) which was dominated by *Ranunculus* sp.

Perhaps unsurprisingly, the four studies differed in their findings. The experiments by Horvath (2004) concluded that particle transport was up to 10 times higher when macrophytes were removed from the channel. This was very different to the outcome of the investigation by Koetsier and McArthur (2000) who determined that S_P values for CPOM within their study were generally greater than those for CPOM within other previous studies, even when *Sparganium* was present. Furthermore, CPOM retention efficiency was generally higher in their vegetated channels during the summer, compared with the unvegetated channels in autumn where retention efficiency was greater. Wanner and Pusch (2001) concluded that macrophyte patches possessed high storage capacities for POM, and the lowest relative trapping efficiency for the tracer particles used within their experimental releases.

The two experimental releases by Warren *et al*., (2009) employed a range of parameters to compare sediment transport between vegetated and unvegetated channels. Their first release compared two adjacent reaches on the same stream with and without vegetation, and their second release was within the same reach with vegetation present and then with all in-channel vegetation removed. The percentage of particles in transport (F_X) was greater in the unvegetated reach (58.2 %) during the first release and greater in the vegetated reach (48.8 %) during the second release. The main difference cited by the authors was the conspicuous presence of colmated gravel during the second unvegetated release combined with lower mean flow velocities flowing vegetation removal. Within their first release K_P was greater within the vegetated reach (0.017 m^{-1}), but the difference between both reaches was comparatively small (± 0.006 m^{-1}). In their second release K_P was greater in the unvegetated reach (0.016 m^{-1}), again with a small difference between the vegetated and unvegetated reaches (± 0.003 m^{-1}). It was difficult to determine if the presence and absence of in-channel macrophytes had directly impacted K_P. Additionally, their results revealed that V_{dep} in release one was considerably greater in their vegetated reach in comparison with their unvegetated, at 1.32 mm $s^{-1}$and 0.40 mm s^{-1} respectively. In comparison, the V_{dep} was greater within the reach when the vegetation was removed (1.50 mm s^{-1}) in contrast to when it was vegetated (1.21 mm s^{-1}) during the second release. Within both releases there were visible differences in the mean flow velocity of the channel and thalweg, as well as mean channel depth between vegetated and unvegetated reaches.

In summary, the results from the two experimental releases by Warren *et al*. (2009) did not present clear-cut results of what direct impact in-stream macrophyte cover has on fine sediment particle transport. But their study did suggest that values of corn pollen K_P and V_{dep} were lower in naturally unvegetated stream channels in comparison with those that are naturally vegetated. Additionally, their second release implied that the presence of vegetation within naturally vegetated channels is more beneficial in terms of sediment transport than when the vegetation is subsequently removed; with corn pollen % retention, in addition to values of K_P and V_{dep} being lower in the reach when vegetation is present. The authors suggested this may have been influenced by the gravel bed being colmated with surficial fine sediment deposits.

In conclusion, it is still difficult to draw an overall consensus as to whether riverine aquatic macrophytes enhance or inhibit fine sediment transport when comparing the results of previous experimental releases within vegetated streams *c.f.* (Wanner and Pusch, 2001; Warren *et al*., 2009). Furthermore, there is currently no long-term work that describes the transport of fine sediment within seasonally-changing vegetated river stretches, including a study that compares one or more periods of annual growth.

2.5 Deposition and storage of fine sediment with rivers and streams

There are several processes of loss occurring within rivers. The overall theory of how sediment particles settle within the water column was discussed by Dobbins (1944), who suggested that the settling of fine sediment particles within a turbulent, fully-mixed water column followed an exponential loss relationship. There are several processes that influence fine sediment deposition and storage within streams and rivers including those where the particle is transformed from one physical state to another (Wotton and Malmqvist, 2001). These processes include natural settling (Dietrich, 1982; Gordon *et al*., 2004), interception by organic and inorganic benthic structures (Weigelhofer and Waringer, 1999), consumption and digestion by fauna (Wotton and Malmqvist, 2001; Wotton *et al*., 1998), colmation (Heppell *et al*., 2009), adhesion (Hall *et al*., 1996) and uncommonly physical destruction (Maciolek and Tunzi, 1968).

There are many natural and anthropogenically-manipulated features within river and stream channels that promote or increase the retention and storage of fine sediment. Much is dependant on the channel planform and geomorphological characteristics, the composition of the river bed and underlying geology, and structural elements present within the river. Sections of lowland rivers and streams have been recognised as important sinks and ephemeral stores of fine sediment (Vannote *et al*., 1980).

2.5.1 Retention, storage and deposition within gravel-bed rivers

Within gravel-bed rivers much of the storage occurs within the gravel or on its surface when particles settle or become sessile due to the near zero flow of the boundary layer on the surface of the substrate (Green, 2005b), and within the interstitial spaces of the bed substrata (Carling, 1984). The study by Walling at al. (2006) on the Pang-Lambourn catchment (England) indicated that 99 % of recently mobilised sediment was subsequently deposited before reaching their measuring stations at the end of the catchment basin.

River beds are a complex matrix of organic and inorganic particles mostly composed of additions of fine sediment from bedload or suspension (Carling and Reader, 1982; Lambert and Walling, 1988). When there is an excess of fine sediment loading and storage, the gravel-bed can become clogged or colmated (Schälchli, 1992). Another form of fine sediment retention within the gravel-bed is the process of armouring, where coarse bed material (>2 mm) overlays and shields fine particles from the flow (Gordon *et al*., 2004).

A number of workers have attempted to analyse the physical characteristics and estimate the deposition and storage of fine sediment particles within gravel-beds. Lambert and Walling (1988) confirmed that there were few empirical studies with detailed field investigations to quantify sediment storage and retention within gravels. Subsequently, they attempted to estimate the stored fine sediment from the surface to the shallow hyporheic of the bed substrate on the River Exe. Their analysis revealed that different estimates of fine sediment storage could be achieved depending on how far down into the gravel samples were taken. Additionally, their study confirmed that the sediment stored within the gravel on the River Exe was composed of 2.8-14.8 % of fine sediment (<2000 µm), of which only 0.4-2.1 % was silt and clay (<63 µm).

The low volumes of fine sediment storage and deposition described by Lambert and Walling (1988) was in agreement with the findings of Cushing *et al*. (1993) and Hunken (2006) who had stated that the period of storage of deposited fine particles is relatively low, with 99 % being resuspended within 24 hours (Cushing *et al*., 1993). However, it also has to be noted that fine sediment storage within the gravel-beds of UK rivers has been demonstrated to be spatially and temporally variable depending on the river in question (Collins and Walling, 2007c). A study on the Rivers Swale and Aire (Scotland) (Walling *et al*., 2003) indicated that only 3 % of fine sediment storage occurred relative to the total flux released, whereas a study on the Rivers Frome and Piddle indicated that storage was 18 and 57 % correspondingly (Collins and Walling, 2007a).

A sediment budget can be constructed when enough information on the river, its catchment and the supply of fine sediment is known. Detailed examination of this is out of the scope of this review, but it is worth highlighting that workers have previously attempted to construct sediment budgets for some UK lowland rivers. These include the Bere Stream (Dorset) (Dawson, 1981), the Rivers Piddle and Frome (Collins and Walling, 2007a), the Rivers Pang and Lambourn (Collins and Walling, 2007c; Walling *et al.*, 2006), the River Tern (Collins and Walling, 2007c) and the River Ouse (Walling *et al.*, 1998).

Many analyses of fine sediment retention and deposition have often taken place in stream reaches that are 'representative' with few abnormal geomorphological or ecological features within the channel. Most natural and semi-natural stream and river reaches possess a considerable amount of within stream features and structures that can lead to the presence of surficial fine sediment deposits.

2.5.2 Surficial fine sediment retention and storage by in-stream structures

The retention and storage of surficial fine sediment in rivers and streams is normally associated with areas of the channel that have lower flow velocities compared to the mean flow velocity (Jones and Smock, 1991). Debris dams in the form of dead wood (Jones and Smock, 1991; Mutz, 2000; Smock *et al.*, 1989; Weigelhofer and Waringer, 1999) and leaves (Scarsbrook and Townsend, 1994; Smock *et al.*, 1989), as well as beaver dams (Butler and Malanson, 2005) and pools within gravel-bed river channels (Lisle and Hilton, 1992; Lisle and Hilton, 1999; Thompson and Wohl, 2009) have been described as areas where fine sediment deposition and surficial storage can occur. Emergent and submergent aquatic macrophytes have also been demonstrated as highly effective retainers and ephemeral stores of fine sediment due to their manipulation of flow velocities within river and stream channels (Butcher, 1933; Clarke, 2002; Cotton *et al.*, 2006; Gurnell *et al.*, 2006; Sand-Jensen, 1998; Wharton *et al.*, 2006).

2.5.3 How do aquatic macrophytes retain and store fine sediment?

Many workers have referred to aquatic macrophytes like *Ranunculus* sp. as biological or ecosystem engineers (Chapin *et al.*, 1997; Corenblit *et al.*, 2007; Cotton *et al.*, 2006; Franklin *et al.*, 2008; Gurnell *et al.*, 2010; Jones *et al.*, 2011; Sand-Jensen, 1998;

Wharton *et al*., 2006). Aquatic macrophytes interact with streamflow to create localised spatial changes in flow velocities and sedimentation patterns (Bennett *et al*., 2002; Butcher, 1933; Cotton *et al*., 2006; Green, 2005c; Gregg and Rose, 1982; Sand-Jensen, 1998; Sand-Jensen and Mebus, 1996; Wharton *et al*., 2006; Wu and He, 2009) and flow hydraulics (Chow, 1959; Gurnell *et al*., 2010; Helmio, 2004; Nepf and Ghisalberti, 2008) within river channels.

Perhaps the most widely reported is the impact of various species of *Ranunculus* sp., particularly within the chalk streams of southern England (Cotton *et al*., 2006; Gurnell *et al*., 2006; Marshall and Westlake, 1990; Wharton *et al*., 2006). *Ranunculus* is one of the most influential river macrophyte species. *Ranunculus* has previously been shown to increase the mean water column depth, modify channel discharges and reduce the mean flow velocities (Hearne and Armitage, 1993). A further impact of the growth of fluvial macrophytes like *Ranunculus* sp. is the constriction of open channel flow into several localised runs of high velocity flow or 'pseudo-braiding' (Dawson and Robinson, 1984) where deposits of fine sediment are absent, and new habitats may be formed (Watson, 2007). This suggests that macrophytes appear to deflect flow around the outer-perimeter of their patch, with eddies being created at the tail of the patch as a result of 'monami' action (Ackerman, 1998; Nepf and Ghisalberti, 2008; Nepf and Vivoni, 2000; Okamoto and Nezu, 2009), and diversion of flow to the opposite bank in experimental channels (Bennett *et al*., 2002) as well as natural channels (Pers. Obs. G. R. Davies, 2008). This has been described previously in vegetated lowland streams (Gurnell *et al*., 2006; Marshall and Westlake, 1990; Sand-Jensen, 1998; Sand-Jensen and Mebus, 1996; Wharton *et al*., 2006).

The presence of vegetation within a channel has been demonstrated to subsequently impact flow and sediment dynamics including increased and decreased spatial variability (Madsen and Warncke, 1983) as well as localised sediment retention and deposition within macrophyte patches and entrainment of sediment particles on their perimeter (Cotton *et al*., 2006; Sand-Jensen, 1998; Watson, 2007; Wharton *et al*., 2006). The greatest change in water flow velocities has been found to occur near the surfaces of macrophyte patches (Gregg and Rose, 1982; Marshall and Westlake, 1990) due to the 'blocking factors' of macrophyte patches (Green, 2006). This perhaps explains why released leaf analogues used by Koestier and McArthur (2000) were observed flowing up and over plant beds without being retained.

In summary, the growth of in-channel aquatic macrophytes leads to the creation of localised zones of highly variable flow within fluvial channels. The retardation of water flows reduces shear and decreases entrainment, which in turn promotes fine sediment accumulation on the river bed within macrophyte patches. Although these effects have been widely reported and acknowledged by a multitude of studies, there is still limited understanding regarding the implications and consequences of macrophyte-flow-sediment relationships within stream channels (Franklin *et al*., 2008).

2.5.4 Estimates of the area, volume and weight of fine sediment deposits within macrophyte beds

Many previous analyses have involved the measurement or estimation of sediment deposition or loading within vegetated river reaches. The first observation of sediment deposition within beds of river macrophytes was made within a study on a chalk river in the UK in the early 1920s (Butcher, 1933). A more recent study on the River Frome and Piddle (Dorset, UK) by Wharton *et al*. (2006) revealed that fine sediment volume per unit area of aquatic macrophytes varied greatly between different locations within the catchment on the same river. Furthermore, Wharton *et al*. (2006) observed that the annual peak and seasonal patterns of fine sediment accumulation within aquatic macrophyte patches were dissimilar between different reaches within the same river.

Heppell *et al*. (2009) estimated and compared fine sediment storage on the Rivers Frome and Piddle. They found that there was a seasonal cycle of fine sediment retention, with the peak occurring from late summer to early autumn with corresponding changes in vegetation cover. An earlier study by Cotton *et al*. (2006) determined there was a similar pattern of sediment retention on the River Frome at Maiden Newton and Pallington. In their study Heppell *et al*. (2009) also revealed that more fine sediment was retained in the River Frome (11.6-66.8 kg m^2), compared to the River Piddle (0.9-23.5 kg m^2) during the same timescale. Considerable fine sediment was present in the unvegetated margins of the River Frome in comparison to the River Piddle even though the margins of the River Piddle had substantial seasonal growths of watercress (hereafter as *Nasturtium*). Heppell *et al*. (2009) also demonstrated that there was greater sediment storage within the margins of the River Piddle when *Nasturtium* had the least percentage cover.

Previous studies of fine sediment deposition and retention at the patch or plant scale have revealed that there are spatial and temporal factors linked to the distribution of fine sediment (Asaeda *et al*., 2009; Cotton *et al*., 2006; Sand-Jensen, 1998; Sanders, 2006). The study by Cotton *et al*. (2006) also analysed spatial and temporal changes of macrophyte patches within a gravel-bed stream. They analysed the change in areal cover of two individual *Ranunculus* patches, each on different rivers, and the associated underlying cover of fine sediment. There were a number of limitations to their study. Firstly, the analysis did not account for changes in the plant rooting zone. Secondly, the analysis period was purposefully short (between April and September 2003) to observe the peak in vegetative growth. Lastly, the analysis only included one representative *Ranunculus* plant per stream. Sand-Jensen (1998) found that different species of macrophytes in a Danish stream produced seasonally and spatially variable distributions of fine sediment characteristics (e.g. particle size within the patch), which he proposed were mostly to do with differing patch size and morphology.

A recent study by Gurnell *et al*. (2010) has indicated that plant species could be grouped in terms of specific morphotypes. Of particular interest in their study were the branched emergents (*Nasturtium*) and submerged patches (e.g. *Ranunculus* sp.), which were found to occupy the same study sites with near similar conditions of sediment deposition and characteristics. This can be compared with the findings of Heppell *et al*. (2009) who found that *Ranunculus* sp. and *Nasturtium* were present together on the Bere Stream (Dorset) in the mid-channel and margins respectively. They also found that *Nasturtium* patches possessed smaller sediment particle size distributions, median particle sizes and higher organic matter than *Ranunculus* patches. This was despite being in the same study reach.

Further long-term (>1 year) studies are required to analyse the spatial and temporal changes in fine sediment deposition within seasonally vegetated streams to allow for comparisons to be made between annual cycles of aquatic macrophyte growth and recession. Additionally, further investigation is still required to analyse seasonal and long-term patterns of sediment storage and volume within individual macrophyte patches.

2.5.5 Patterns of fine sediment particle characteristics within aquatic macrophyte patches

Spatial changes in particle size distribution within macrophyte patches were first examined on a Danish sand-bed stream by Sand-Jensen (1998). He found that particle size distributions strongly corresponded to the location within plant patches, and became generally finer and less variable within the upstream two-thirds of macrophyte beds. Conversely, more coarse and variable fine sediment was found on the outside of macrophyte patches, and particle sizes in sediment depths from 5 to15 cm resembled the sediment particle size distributions in the surface 1 cm layer found outside of macrophyte patches. The median particle sizes (D_{50}) within the four species of plants were within the fine to medium sand from 175 to 448 μm. However, his work is not directly comparable to the studies from gravel-bed streams due to differences in the characteristics of the bed substratum.

There have also been analyses of the particle size distributions of sediment underlying aquatic macrophytes within chalk streams. Cotton *et al*. (2006) explored the changing seasonal pattern of absolute particle size within the fine sediment underneath *Ranunculus penicillatus* var. *calcareous* ((R.W. Butcher) C.D.K. Cook) on two reaches of the River Frome (Dorset, UK). Their study found that sand-sized particles (63-1000 μm) dominated the particle size distributions under the representative *Ranunculus* patches. Furthermore, silt and clay (<63 μm) was approximately <15 % of the volume within sediment samples. A comparative study by Wharton *et al*. (2006) on the effective particle size distribution of the sediment underlying *Ranunculus* patches on the River Piddle (Dorset, UK) found that the particle size distributions were also mostly dominated by sand-sized sediment, but samples were composed of greater proportions (6-48 %) of silt and clay sized particles.

A further study by Heppell *et al*. (2009) on the Frome-Piddle catchment analysed the particle size distributions and median particle sizes of effective and absolute sediment underlying macrophytes within the channel margins and mid-channel zones. Their study revealed that the effective and absolute fraction of sediment from vegetated mid-channel zones were dominated by the fine to medium sand (125-500 μm) on the River Frome, and by very fine to medium sand (63-500 μm) on the River Piddle. The median particle size of the effective sediment fraction within the vegetated mid-channel of the River Piddle was comparable to that of the River Frome. However, the overall particle size distribution on the River Piddle possessed a greater range of particle sizes from the very fine to medium sand. The median particle size of the absolute fraction in the vegetated mid-channel zone was found to be within the medium sand, and the particle size distribution was greater than that of comparable samples from the River Frome and the effective fraction on the River Piddle.

Marginal areas of the River Frome had median particle sizes and particle size distributions from very fine to fine sand (63 to 125 μm). The effective fractions of the samples from the marginal areas of the River Piddle were comparable to that of the effective and absolute margin samples from the River Frome. The absolute median particle size and range of the particle distribution from the River Piddle was represented by medium silts to very fine sand (16 to 125 μm). Heppell *et al*. (2009) suggested that there were differences between effective and absolute median particle sizes and particle size distributions in the margins on the River Piddle for two reasons. Firstly, there was a possible difference in the aggregate composition of the retained matter, and secondly the growth of the *Nasturtium* had possible influences on the aggregation of the silt-clay component within the deposited fine sediment.

It is apparent that further work is required to understand how macrophyte patches control the quantity and character of retained fine sediment within their patches. More plant-scale work within *Ranunculus* and *Nasturtium* patches is required to observe and interpret spatial and temporal changes of particle characteristics of the fine sediment that is retained and stored within the mid-channel zones of chalk streams. Additional analyses are required to understand how *Nasturtium* influences sediment characteristics in streams where it is co-dominant or the dominant species. Further analyses of sediment particle sorting are required to further analyse the effects of macrophytes on sediment particle distribution and sorting. The use of a sorting coefficient would most likely be the best way of conveying the degree of sorting within a sediment sample. The Trask sorting coefficient (S_0) (Trask, 1932) is satisfactory for observing the sorting of sediment that is generally well sorted (Friedman, 1962). Previous workers have highlighted that sediment samples within plants in UK chalk streams are mainly composed of sand-sized particles from 63 to 2000 μm (Cotton *et al*., 2006; Sand-Jensen, 1998; Wharton *et al*., 2006).

Furthermore, there are currently only a few studies where individual patches of macrophytes have been arbitrarily segmented (*c.f.* Sand-Jensen and Pedersen (1999);

Sanders (2006) to analyse differences in sediment characteristics as well as fine sediment retention and volume. Further study of the spatial and temporal changes in fine sediment characteristics within individual macrophyte patches is required.

2.6 The geography, morphology and lifecycle of aquatic *Ranunculus* species

There are close to 600 species of terrestrial and aquatic plants within the genus *Ranunculus* (buttercups) (Lumbreras *et al*., 2009) inhabiting all continents except Antarctica (Lumbreras *et al*., 2011). The 17 species of aquatic and semi-aquatic *Ranunculus* plants found within inland waterbodies of many countries within Europe and Asia (Lumbreras *et al*., 2009). Inland freshwater habitats that possess submerged or floating macrophytes like *Ranunculus* communities are priority habitats of international importance and are listed under Annex II of the EU Habitats Directive (92/43/EEC) (Hatton-Ellis and Grieve, 2003).

According to Haslam *et al*. (1982) there are eleven distinct species of aquatic *Ranunculus* within the British Isles, all are white-flowering plants with the exception of *Ranunculus flammula and Ranunculus sceleratus (Lumbreras et al., 2011)*. The geographical distribution of each species and subspecies is habitat-specific and dependent on the physical and chemical conditions of the waterbody they inhabit (Table 2.2) (Haslam, 1987; Haslam *et al*., 1982; Lumbreras *et al*., 2011; Lumbreras *et al*., 2009; Mony *et al*., 2006).

On first inspection there appears to be little difference in between species, so much so that it is often difficult to differentiate between individual species, hybrids and intermediate plants. Individual species are identified by observing the length, structure and number of stems, nodes, internodes, capillary leaves and broad (laminar) leaves in addition to fruiting bodies and flower structure (Haslam *et al*., 1982; Lumbreras *et al*., 2011). Additionally, some *Ranunculus* plants are submerged for the majority of their lifecycle, while others float or emerge slightly above the waters' surface (Table 2.2).

All growing aquatic *Ranunculus* plants are anchored to the channel bed by a network of rhizomes and roots that curl around gravels and grains of course sand. The thick, flexible and tube-like stems of *Ranunculus* plants can be greater than 1 m in length for some species at peak growth (G. Davies Pers. Obs. 2010). In general all

Table 2.2 - A table of the 15 semi-aquatic and aquatic species of *Ranunculus* found within the UK with their physiological, morphological and habitat characteristics. [1] – Haslam (1987); [2] – Haslam, *et al*. (1982); [3] - (1999a); [4] – Holmes, *et al*. (1999b); [5] – Webster (1988); [6] – Lumbreras, *et al.* (2011), and [7] – Cook and Johnson, (1968).

Species/subspecies/variety	**UK Habitats[1,2,3]**	**Present within chalk streams[3,4]?**	**Flow regime[1,2,3,5]**
Ranunculus aquatilus (L.)	Streams	Y	Still, slow to fast
Ranunculus baudotii (Godr.)	Pools, dykes	N	Still to slow
Ranunculus circinatus (Sibth.)	Ponds, canals, dykes, small streams	Y	Still to slow
Ranunculus flammula (L.)	Lakes, ponds, upland streams	Y	Still to fast
Ranunculus fluitans (Lam.)	Highland streams, lowland streams	Y	Moderate to swift
Ranunculus hederaceus (L.)	Pools, ditches, small streams	N	Still to moderate
Ranunculus omiophyllus (Ten.)	Pools, ditches, small streams	Y	Still to slow
Ranunculus peltatus (Schrank)	Pools, ponds, dykes, shallow streams	Y	Still to swift
Ranunculus peltatus subsp. *pseudofluitans* (Syme) S.D. Webster	Lowland streams	Y	Moderate to swift*
Ranunculus penicillatus subsp. *penicillatus* (Dumort.) Bab.	Highland rivers, lowland streams	Y	Moderate to swift
Ranunculus penicillatus var *calcareus* (Butcher) C.D.K. Cook	Streams	Y	Moderate to fast
Ranunculus penicillatus var *vertumnus* (C.D.K. Cook)	Streams, rivers	Y	Slow
Ranunculus sceleratus (L.)	Ponds, ditches	Y	Still to slow
Ranunculus trichophyllus (Chaix)	Ponds, dykes, canals, shallow streams	Y	Still to moderate
Ranunculus tripartitus (D.C.)	Ponds, ditches	N	Still to slow

Species/subspecies/variety	**Rooting substrate[1,2]**	**Leaf types[6,7]**	**Emergent/Floating/Submergent[1,2,3]**
Ranunculus aquatilus (L.)	Fine to course mineral and organic	Heterophyllous	Submergent, floating
Ranunculus baudotii (Godr.)	Fine	Heterophyllous	Submergent, floating
Ranunculus circinatus (Sibth.)	Fine and organic	Homophyllous	Submergent
Ranunculus flammula (L.)	Fine to course mineral and organic	Heterophyllous	Emergent, submergent
Ranunculus fluitans (Lam.)	Medium to course	Heterophyllous	Submergent
Ranunculus hederaceus (L.)	Sandy with an organic top layer	Homophyllous	Floating
Ranunculus omiophyllus (Ten.)	Fine and organic	Homophyllous	Floating
Ranunculus peltatus (Schrank)	Fine to course mineral and organic	Heterophyllous	Submergent, floating
Ranunculus peltatus subsp. *pseudofluitans* (Syme) S.D. Webster	Medium to course	Heterophyllous	Submergent, floating
Ranunculus penicillatus subsp. *penicillatus* (Dumort.) Bab.	Fine to course	Heterophyllous	Submergent
Ranunculus penicillatus var *calcareus* (Butcher) C.D.K. Cook	Medium to course	Heterophyllous	Submergent
Ranunculus penicillatus var *vertumnus* (C.D.K. Cook)	Medium to course	Heterophyllous	Submergent
Ranunculus sceleratus (L.)	Fine mineral to organic	Heterophyllous	Emergent, submergent
Ranunculus trichophyllus (Chaix)	Varied substrate	Homophyllous	Submergent, floating
Ranunculus tripartitus (D.C.)	Fine mineral to organic	Heterophyllous	Submergent, floating

Ranunculus plant stems and leaves are a deep or olive green in colour. The top canopy of the plant is free flowing and the tail end sways in the presence of turbulent flow, this is also known as the monami effect (Ackerman, 1998; Nepf and Ghisalberti, 2008; Nepf and Vivoni, 2000; Okamoto and Nezu, 2009). As a result a streamlined and tapered shape is formed to reduce drag against ambient flowing water (Green, 2005a; O'Hare *et al*., 2007a; Sand-Jensen, 2003; Sand-Jensen and Pedersen, 1999; Statzner *et al*., 2006).

Aquatic *Ranunculus* plants receive the sustenance through absorbing nutrients in the interstitial water as well as absorbing nutrients through their roots and rhizomes (Barko *et al*., 1991; Boeger, 1992). Furthermore, it has been suggested that *Ranunculus aquatilis* and other submerged plants inhabiting mineral-rich watercourses are more than capable of receiving the majority of important nutrients such as nitrogen and phosphorus though their leaves and stems (Madsen and Cedergreen, 2002).

Most plants are unable to persist over the winter period due to physical removal by increased discharge (Butcher, 1933). The reproduction of aquatic *Ranunculus* is generally split between seasonally determined asexual reproduction by the breaking off of stems and uprooting of rhizomes and dispersal by hydrochory, and sexual reproduction through the pollination of flowers and dispersal of seeds (Barrat-Segretain and Bornette, 2000; Johansson and Nilsson, 1993). Currently, there has been uneven attention paid to individual species that has left gaps in knowledge regarding reproductive cycles within individual *Ranunculus* species (Hatton-Ellis and Grieve, 2003; Lumbreras *et al*., 2011).

Peak annual growth, productivity and biomass of *Ranunculus* species habiting chalk streams and rivers is during the middle to late summer months due to the increased levels of light leading to increased photosynthesis (Cotton *et al*., 2006; Dawson and Kernhansen, 1979; Wharton *et al*., 2006). *Ranunculus* cover within chalk rivers generally declines from summer to winter and remains low until the following spring.

2.7 Summary

This review of the current literature has acknowledged previous studies that have investigated the spatial and temporal impact of in-channel macrophytes on the trapping and retention of fine sediment. Further studies are now required to increase our understanding of the role of aquatic macrophyte growth on the reach-scale transport of fine sediments using analogues. Particle analogues are beneficial for studying fine sediment transport due to their comparative particle characteristics with fine sediment, conspicuous appearance within samples and ease of deployment in the field.

Additionally, there are no clear guidelines for effectively managing macrophyte patches within rivers to encourage increases in fine sediment transport as well as water conveyance. The development of an index or measure of fine sediment conveyance in relation to the amount of macrophyte cover or volume within a river channel could be beneficial to inform management of lowland vegetated rivers.

Riverine macrophytes have been implicated as efficient retainers and stores of fine sediment within previous studies. But many of these studies have focused solely on the retention and storage of fine sediment relating to the morphology of macrophyte patches as well as their impact on water flow velocities. Further detailed work is required to understand the spatial and temporal patterns of fine sediment characteristics and volume at the reach scale in relation to seasonally-changing macrophyte cover.

Furthermore, there are only a few workers who have attempted to investigate the fine sediment characteristics within individual macrophyte patches growing naturally within river and stream channels. But additional detailed analyses are required to observe the spatial and temporal patterns of deposited fine sediment characteristics and volume within individual macrophyte patches in relation to seasonal patch growth.

Additional information on fine sediment deposition within vegetated streams at the reach and patch-scale will increase understanding relating to fine sediment transport and aquatic vegetation management within lowland gravel-bed rivers.

2.8 Research aims & specific questions

The overall aim of this research was to investigate the role that seasonally-changing macrophyte cover has in the transport, deposition and storage of fine sediment at the reach scale and plant scale within two lowland permeable streams. The following are the research aims and specific research questions:

1. **To investigate the influence of seasonally-changing macrophyte cover on fine sediment deposition and storage at the reach scale within two lowland permeable streams.**

- How do seasonal changes in macrophyte cover impact spatial and temporal patterns of fine sediment depth, volume and sediment particle characteristics at the reach scale?
    1. H_0 – Seasonal changes in total macrophyte cover and the spatial arrangement of macrophytes do not influence seasonal patterns fine sediment retention and storage.

       H_1 – Seasonal changes in total macrophyte cover and the spatial arrangement of macrophytes do influence seasonal patterns fine sediment retention and storage.
    2. H_0 – The physical characteristics of fine particulate sediment do not vary on a seasonal basis within *Ranunculus* patches at the reach scale.

       H_1 – The physical characteristics of fine particulate sediment do vary on a seasonal basis within *Ranunculus* patches at the reach scale.
    3. H_0 – The retention of fine sediment does not differ between different macrophyte species at the reach scale.

       H_1 – The retention of fine sediment does differ between different macrophyte species at the reach scale.
    4. H_0 – The retention of fine sediment does not differ between emergent and submergent *Ranunculus* the reach scale.

       H_0 – The retention of fine sediment does differ between emergent and submergent *Ranunculus* the reach scale.
    5. H_0 – There are no differences between the two lowland streams in relation to seasonal fine sediment storage and volume at the reach scale.

       H_1 –The two lowland streams show seasonal differences in fine sediment storage and volume at the reach scale.

2. **To analyse the impact of seasonally-changing macrophyte cover on fine sediment transport at the reach scale within two lowland permeable streams.**

- How do seasonal changes of macrophyte cover and composition influence fine sediment transport at the reach scale?
    i. H_0 – The seasonal changes in total macrophyte cover do not influence fine sediment transport parameters at the reach scale.

       H_1 – The seasonal changes in total macrophyte cover do influence fine sediment transport parameters at the reach scale.

    ii. H_0 – The cover and distribution of individual macrophyte species do not influence fine sediment transport parameters at the reach scale.

        H_1 – The cover and distribution of individual macrophyte species do influence fine sediment transport parameters at the reach scale.

    iii. H_0 – There is no differences between the two lowland streams in this study regarding fine sediment transport in relation to seasonal macrophyte cover and distribution.

         H_1 – There is a difference in between the two lowland streams in this study regarding fine sediment transport in relation to seasonal macrophyte cover and distribution.

- Can measurements of leakiness or channel porosity be used to estimate fine sediment transport within vegetated lowland streams reaches?
    i. H_0 – Seasonal variations in channel porosity are not influenced by corresponding values of seasonally changing macrophyte cover at the reach scale.

       H_1 – Seasonal variations in porosity are influenced by corresponding values of seasonally changing macrophyte cover at the reach scale.

    ii. H_0 – Seasonal variations in channel porosity do not influence fine sediment transport parameters at the reach scale.

        H_1 – Seasonal variations in channel porosity have an influence on fine sediment transport parameters at the reach scale.

3. **To examine the temporal and spatial changes of fine sediment deposition and particle characteristics within *Ranunculus* patches.**

- How does the deposition and storage of fine sediment change in relation to seasonal changes in *Ranunculus* patch area and volume?
    i. H_0 – Seasonal fine sediment deposition and storage within *Ranunculus* patches is not influenced by corresponding changes in patch cover and volume.
    H_1 – Seasonal fine sediment deposition and storage within *Ranunculus* patches is dependent on corresponding changes of patch cover and volume.

- Are there any differences between *Ranunculus* patches of the same species in relation to fine sediment particle characteristics?
    i. H_0 – Fine sediment particle characteristics do not vary between individual *Ranunculus* patches.
    H_1 – Fine sediment particle characteristics vary between individual *Ranunculus* patches.

- What are the spatial and temporal patterns of fine sediment particle characteristics within specific zones of *Ranunculus* patches?
    i. H_0 – Fine sediment particle characteristics do not vary between different zones within *Ranunculus* patches over time and space.
    H_1 – Fine sediment particle characteristics do vary between different zones within *Ranunculus* patches over time and space.

CHAPTER 3

Methodology

3.0 Introduction

This chapter begins with a description of the field site selection criteria and a description of the field sites chosen for the study (section 3.1). Following this is a structural diagram of the field, laboratory and data analyses that were employed for each of the three aims within this study (section 3.2). The chapter is then divided into two main sections. Sections 3.3 to 3.6 inclusive describe the survey data collection and procedures employed for taking samples of fine sediment and water. Sections 3.7 to 3.10 detail the methods used to analyse samples within the laboratory, data syntheses involving GIS and data analyses.

3.1 Study sites

3.1.1 Selection of study sites

The selection of study sites was restricted to all of the lowland chalk stream catchments in the south of England. Of special interest were those rivers and streams where previous studies had described *Ranunculus* as the dominant macrophyte species. Two watercourses of high and low order were required to provide a comparison of two stream reaches. It was important that the catchments and rivers were as analogous as possible with regarding bedrock geology and physical and chemical composition. A concise list of gauging stations was also consulted to ensure it was appropriate to work on some sections of rivers (for further details please refer to http://www.ceh.ac.uk/data/nrfa/uk_gauging_station_network.html).

The Frome and Piddle catchments in southern England were selected as the study catchments. The majority of both catchments overlay the same Cretaceous chalk geology and drain from permeable groundwater-fed aquifers (Dawson, 1976; Wharton *et al.*, 2006). Furthermore, the catchments are located next to each other which simplified fieldwork logistics. The annual growth of *Ranunculus*-dominated macrophyte communities had previously been documented on both rivers (Cotton *et al*., 2006; Dawson, 1976; Dawson, 1981; Dawson and Kernhansen, 1979; Wharton *et al*., 2006), and both river catchments had been included within the recent NERC-sponsored LOCAR programme (http://www.nerc.ac.uk/research/programmes/locar/) between 2000 and 2006. This meant that there was sufficient background data available for comparison with the findings of this study.

Study reaches were chosen carefully, based on specific requirements of this research. The prospective study sites would differ in aquatic macrophyte cover. One site was selected for species-rich macrophyte cover, while the other was selected for possessing dominant *Ranunculus* cover. The intention of this was to provide a comparison between two stream reaches where one was dominated by *Ranunculus* patches, and the other possessed a number of different macrophyte species. A list of possible study sites along both rivers and their tributaries was generated using existing literature and referring to an OS Explorer map (1: 25,000). From the map it was possible to assess potential problems associated with sites such as access to land, landowner permission, land-use, terrain and proximity to roads. Furthermore, it was also possible to assess if sites would be safe to work on regarding wild animals and livestock. The proximity of the sites to populated areas was also considered to minimise vulnerability of the study reaches to anthropogenic perturbations, including the likelihood of vandalism to deployed equipment.

A reconnaissance visit to the two catchments was made in December 2007. As a result Snatford Bridge on the Bere Stream and Frome Vauchurch on the River Frome were chosen as the study sites (Figure 3.1). These two sites were selected because they were relevant to the stream comparison criterion in that they were of different were of different stream order, and they possess similar physical and chemical composition. Additionally, previous macrophyte-flow-sediment work has been conducted on these rivers, including experimental field work for the recent LOCAR programme. Additionally, the sites were open from tree cover, and possess healthy seasonal growth of *Ranunculus* patches (Wharton *et al*., 2006). The study reaches had little sinuosity with no particular geomorphological features such as braiding or mid-channel bars. This made them directly comparable with no complications due to geomorphological features being apparent at the start of the study. Both sites were wadeable and accessible throughout the year which ensured that surveys, measurements and experimental releases could be safely conducted. The difference in hydromorphological conditions

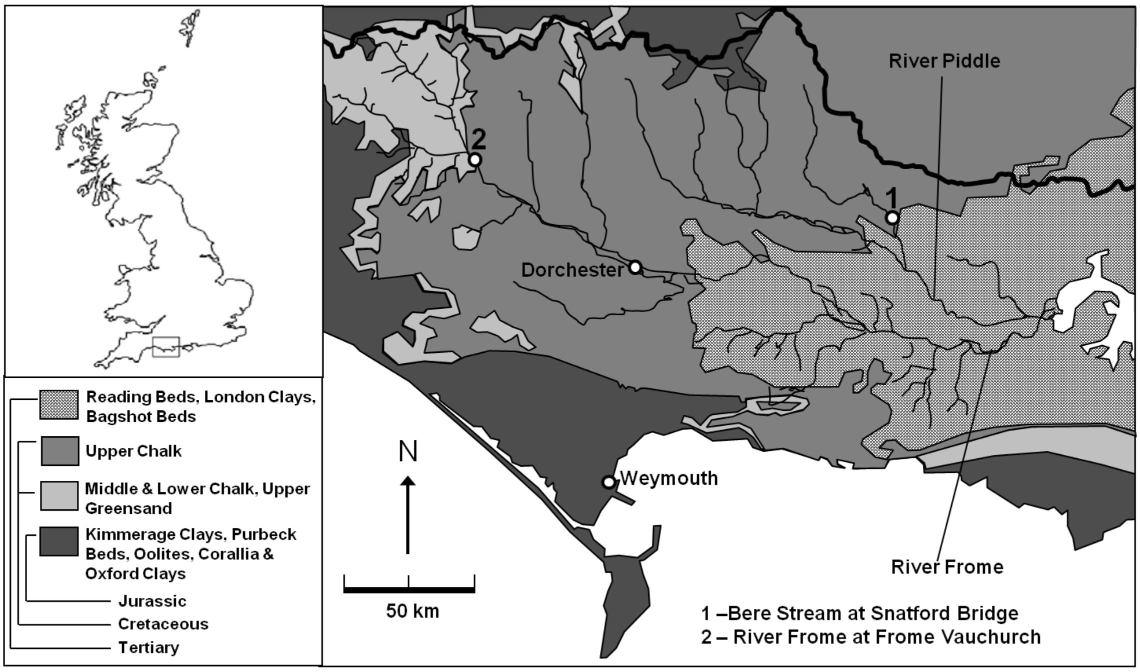


Figure 3.1 - A map illustrating the geographic location of the Piddle-Frome catchments (Dorset, England) and their main geological bed formations redrawn from Wharton *et al*. (2006). The location of the two field sites are illustrated on the Bere Stream and River Frome.

between the two sites also added a further dimension to the study. The River Frome at Frome Vauchurch possesses a 'flashy' hydrological response, in comparison to the Bere Stream which has a slower hydrological response (Dawson, 1981; Wharton *et al*., 2006).

3.1.2 Frome Vauchurch on the River Frome

The site at Frome Vauchurch (SY5978797399) (Figure 3.2) is a 30 m reach of the 3rd stream order channel of the River Frome that flows from Cattistock. The River Frome is joined by the River Hooke tributary at Maiden Newton, which is approximately 300 m upstream of Frome Vauchurch. The site overlays the Cretaceous Upper Chalk, with water and sediment supplied from Jurassic limestone, Upper Greensand, Chalk and Tertiary deposits (LOCAR Task Force Report – see http://www.nerc.ac.uk/locar, Cotton *et al*., 2006). The surrounding land use at the time of the study was predominantly pastoral-rural with a few surrounding villages and towns.

The site is adjacent to a local footpath and a minor road on the right bank, with a road bridge approximately 100 m upstream of the study reach. The channel banks were characterised as possessing a shallow vertical profile with some localised under-cutting.

Marginal terrestrial vegetation was dominated by butterbur (*Petasites hybridus* L. Gaertn., Mey. & Sherb.), bramble (*Rubus fruticosus* L.), nettle (*Urtica dioica* L.) and *Oenanthe* sp. These lined the banktops of the channel and commonly intruded into the flow during the summer months. Partial tree cover was provided on the left bank by riparian shrub and deciduous trees. The study reach had a mean channel width of 9.0 m and a mean water depth of 0.43 m over the two years.

The river bed was formed of a patchwork of flint with fine and coarse gravels (Wharton *et al*., 2006) with smaller patches of filamentous benthic algae, as well as larger emergent and submergent water crowfoot (*Ranunculus* sp.) patches. The dominant species of *Ranunculus* was stream water-crowfoot (*R. penicillatus subsp. pseudofluitans* (Syme) S.D. Webster). Single sparse patches of other aquatic macrophytes that were present within the survey period included alternate-flowered water-milfoil (*Myriophyllum alterniflorum* DC.) and starwort (*Callitriche* sp.).

Figure 3.2 - Photographs of The River Frome at Frome Vauchurch (A), and the Bere Stream at Snatford Bridge (B). Both photographs were taken in May 2009 looking upstream from the most downstream cross-section. Photographs taken by G. Davies.

3.1.3 The Bere Stream at Snatford Bridge

The study site is a 30 m reach located on the Bere Stream at Snatford Bridge (SY8557092999) (Figure 3.2), which is a 1st order main tributary stream of the River Piddle. The stream overlays Cretaceous Upper Chalk geology (Dawson, 1976) and is predominantly groundwater-fed. It is situated directly upstream of Snatford Bridge and 1.75 km from the River Piddle-Bere Stream confluence (Wharton *et al*., 2006). Land use in the surrounding area was predominantly pastoral agricultural, with the exception of a commercial watercress farm that was located approximately one mile upstream of the reach at the time of this study.

The site is a straight section of the stream with a low bank profile on both sides. The banks were dominated by overhanging terrestrial vegetation, composed in the majority of *Oenanthe* sp., water parsnip (*Berula erecta* (Huds.) Coville) and *Urtica dioica*. Growth of *Berula erecta* and *Oenanthe* made up smaller proportions of the marginal vegetation in the summer months and occasionally led to their encroachment into the stream. The majority of marginal aquatic vegetation present throughout the survey period was watercress (*Nasturtium officinale*), with considerable growths of fool's watercress (*Apium nodiflorum* (L.) Lag). The reach was generally open from cover except for an oak tree (*Quercus rubra* L.) in the upper part of the reach. The study reach had a mean channel width of 6.8 m and mean water depth of 0.29 m over the two year period.

The channel bed was composed of flints and fine to coarse gravels (Wharton *et al*., 2006). Aquatic macrophytes within the channel included emergent and submergent *Ranunculus*. The two dominant species of *Ranunculus* within the reach during the study were *R. penicillatus subsp. calcareous* (R.W. Butcher) C.D.K. Cook and *R. penicillatus subsp. pseudofluitans,* with the latter being the most dominant species.

3.2 Structure of methodology

The structure of this thesis is based around the three research aims that were stated previously in Chapter 2. The outline of the methodology for this thesis is depicted in Figure 3.3, which provides a breakdown of the field, laboratory and data analyses for each of the three research aims within this study.

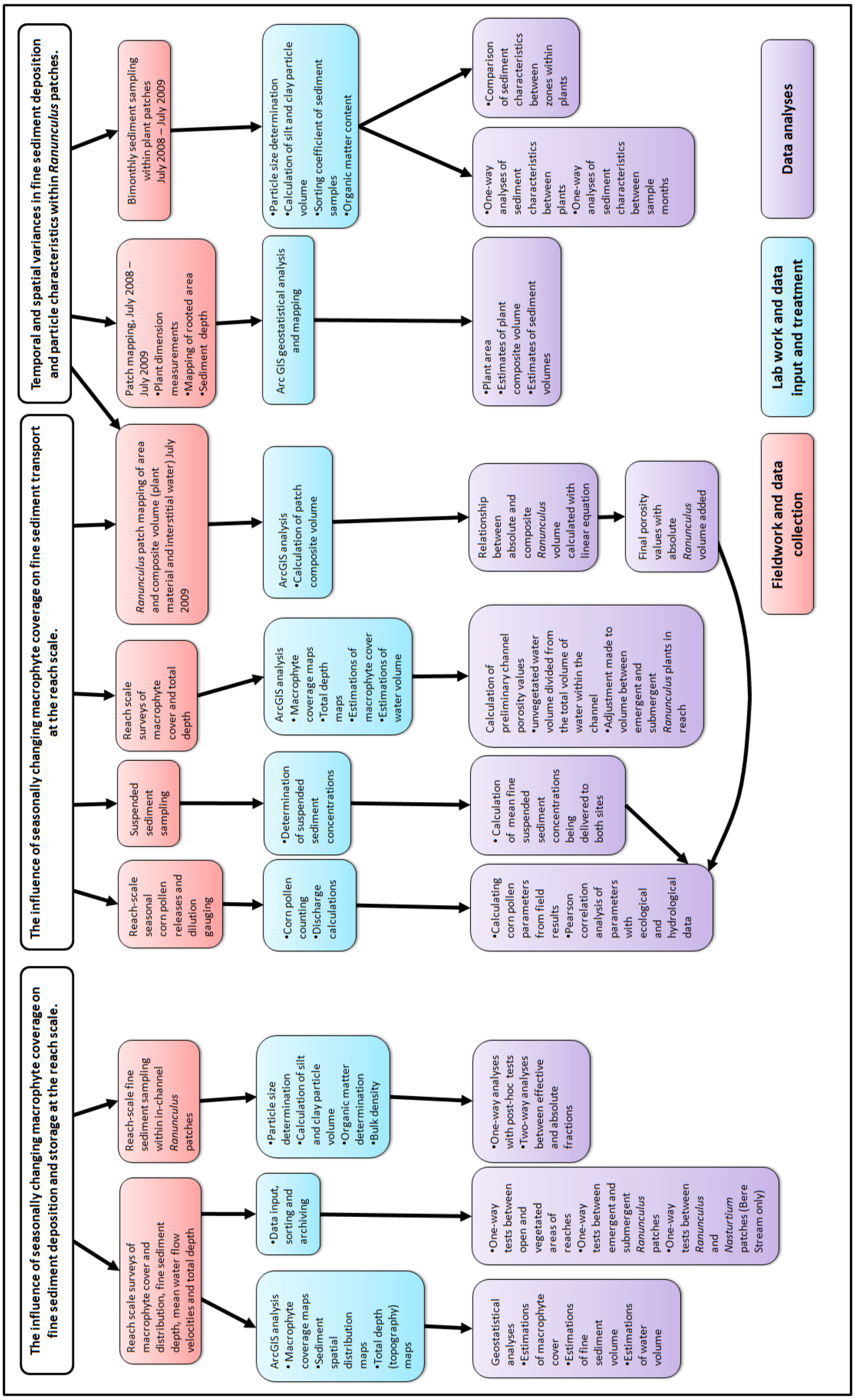


Figure 3.3 – The structure of the methodology of this thesis. The methodology is split into the three research aims. Under each research aim the methodology forms three main components including: (1) Fieldwork and data collection, (2) Laboratory work and data input, and (3) Data analyses.

3.3 Seasonal experimental corn pollen releases

3.3.1 Corn pollen characteristics and preparation

Corn pollen has been used previously by other workers as an analogue for natural fine particulate sediment (Broekhuizen and Quinn, 1998; Georgian *et al*., 2003; Miller and Georgian, 1992; Warren *et al*., 2009; Webster *et al*., 1999). Corn pollen is inert and can be easily pre-stained with dye before release. This process produces individual grains that are more conspicuous in samples (Warren, 2006; Warren *et al*., 2009). The staining process does not alter the physical characteristics of the corn pollen grains (Georgian *et al*., 2003).

A study by Georgian *et al*. (2003) compared the transport of corn pollen (87 ± 4.9 (SD) μm) and natural fine particulate sediment (53-106 μm) within a mountain stream. They found that there was little difference between the transport and deposition of the two particles within their study stream. This led them to suggest that corn pollen particles are a suitable surrogate for natural fine particulate sediment.

Corn pollen (Polysciences, Inc.) was chosen as the analogue for natural fine particulate sediment within this study. The particle characteristics of corn pollen include mean particle diameter of 87 ± 4.9 (SD) and a particle density of 1213 ± 43.6 (SD) kg/m^3. Each supplied vial contained approximately 1 g of corn pollen, this is equal to 2.6×10^6 grains when calculated using Stokes Law (Vogel, 1994). Each 1 g vial contained enough grains per seasonal release per stream. Corn pollen grains within each release were made identifiable by a process of dying that was modified from a previous method (Zangerl *et al*., 2001). Each corn pollen sample was dyed one day prior to the actual release. The dye mixture was prepared from 20 ml commercially available food colouring (Dr Oetker), 5 ml glycerol, 10 ml ethanol and 5 ml of water. This was placed in a 50 ml centrifuge tube and shaken at room temperature for approximately 5 minutes to ensure thorough mixing of all the constituents. A single 1 g vial of corn pollen was then added into the dye mixture, and the centrifuge tube was again shaken for approximately 30 minutes on its side to allow for maximum exposure of corn pollen to the dye mixture. A different colour dye was used for each seasonal release to ensure positive identification of corn pollen grains released. The permanence of the dyes were tested in the laboratory by batch dying prior to the start of experimental releases to test the solubility of the dye colours in water (Figure 3.4)

Figure 3.4 – Corn pollen particles that have been dyed in a range of conspicuous colours using commercially available food dyes. Corn pollen particles within these samples appear aggregated due to shaking and stirring. Photograph taken by G. Davies.

3.3.2 Reach-scale experimental releases of corn pollen

The impact of changing seasonal macrophyte growth on fine sediment transport was investigated using reach scale corn pollen releases. Seasonal reach scale releases of corn pollen were conducted every two months from July 2008 to July 2010 at Snatford Bridge on the Bere Stream, and from September 2008 to July 2010 on the River Frome at Frome Vauchurch. Each release of corn pollen was preceded by a measure of the passage of NaCl solution through the reach by chemical dilution gauging.

The mean channel flow velocity and required frequency of water sampling downstream was determined by salt dilution gauging prior to the release of the dyed corn pollen slug. A standard chloride (Cl^-) slug was used for each release. This comprised of 10 kg of granular table salt (NaCl) placed into a dustbin and dissolved in approximately 60 l of stream water at the top of the reach. The solution was thoroughly stirred to ensure that all of the salt granules had dissolved into solution. The solution was carefully taken to the release station within the reach. The release station was in the middle of the stream cross-section, and approximately 30 m upstream from the downstream sampling station at each site. The 30 m section of both reaches used for experimental releases was the same part of the reach surveyed for macrophyte cover.

The salt solution was added into the thalweg in one 'gulp'. The thalweg had been identified previously in reach surveys prior to the release. The change in electrical conductivity (EC, $\mu S\ cm^{-1}$) was measured using a hand-held conductivity probe (Hanna HI 8733) at both the upstream release point and downstream sampling station of the reach. The release and sampling points remained the same for each release. The release of the gulp was timed with a stopwatch and a measurement of EC made every 5 seconds, initiated by a blow of a whistle. Measurements continued until EC had returned to background levels at the downstream station. The sampling frequency of water samples for each release was determined by analysing the passage of EC within the streamflow at the downstream station at each site.

A standard corn pollen and dye slug was prepared in a bucket of 10 l stream water. The slug was deposited as a 'gulp' into the thalweg at the upstream release point and timed from release. Timed 'grab' samples were taken at the downstream station in 10 second intervals at the start of the EC recordings, in 5 second intervals during the peak in EC recordings, and at 10 second intervals following the decrease in EC from the peak to background. Grab samples were made with 1 l (8 cm aperture) bottles in the thalweg of the stream. Each bottle was angled at 45 ^{o} to allow for air displacement during sampling. Water samples were taken at approximately 0.6 of the water column depth.

3.4 Reach scale surveying and mapping

The extent to which macrophyte abundance and distribution is recorded within rivers and streams depends on the criteria of the individual study (Wright *et al*., 1981). Many studies within streams and rivers rely on a form of mapping designed to record and estimate macrophyte and sediment distribution, for which a number of methods have been developed within rivers and streams. The types of measurement fall into two main categories which are (1) mapping from measurements made at datum, and (2) mapping measurements made using satellite or aerial photography.

Measurements made at datum were the first to be developed. The first known mapping of macrophyte cover within a river channel was on the River Ivel (Butcher, 1933) which consisted of 2D sketch mapping like that of the 'detailed' mapping method. This form of mapping remains a quick and easy form of recording macrophyte data within river channels and small lakes. A similar approach was taken by Holmes and Whitton (1977a; 1977b) on the River Tees and River Swale. A review of mapping methodology for river macrophytes was conducted by Wright *et al*. (1981) who compared the two main methods which were then in use. One was the detailed method used by Butcher (1933) and the other was a rectangle method that had been refined from the detailed method. Both techniques relied on the collection of macrophyte abundance data within the stream to produce coverage maps.

The resulting output of the detailed method was maps of macrophyte cover and distribution resembling those by Butcher (1933). The rectangles method output represented macrophyte cover in a cruder way, being composed of rectangles of 1 x 0.5 m resolution, which resembling a simple raster cell map. This type of mapping has been used by other subsequent workers for providing relatively quick macrophyte area cover estimates (Ham *et al*., 1982; Welton, 1980). A notable example was produced by Gurnell *et al*. (2006) for mapping macrophyte abundance, sediment depth and other parameters on the River Frome, Dorset. Other successful ground-based mapping methods have since been deployed for recording aquatic vegetation and other in-stream features, such as photographic collages (Cotton *et al*., 2006; Mutz, 2000) and electronic survey measurements (EDM) taken with a total station (Mutz, 2000; Sanders *et al*., 2007; Wharton *et al*., 2006).

Most mapping produced at datum is accurate and easy to implement, with the accuracy of simple surveys including tape measures being acceptable up to 5 % error (Gordon *et al*., 2004). The disadvantages or limitations of ground-level survey methods include among others: (1) the time consuming nature of surveys; (2) the physical and logistical impossibility of some surveys due to the location of the watercourse; (3) possible limitations due to large longitudinal and cross-sectional dimensions of the channel; (4) the health and safety aspect with regards to channel flow, and lastly (5) post-processing and data input of survey results.

In some instances due to the circumstances described above it is more practical to use aerial photography, remote sensing or satellite imagery methods e.g. Ashraf *et al*. (2010), to map river channel geomorphology and associated vegetation. The first documented use of aerial photography to map river vegetation was by Edwards and Brown (1960) on the River Ivel, who used a suspended camera attached to a balloon that was tethered to a rowing boat. Methods of aerial-sourced mapping are becoming increasingly popular due to the improvement of associated methodologies, technology and equipment, as well as geospatial accuracy. However the inherent problems of aerial photography include: (1) the cost of equipment; (2) photographic warping; (3) lack of automatic scale and geo-referencing; (4) glare from the waters' surface; (5) riparian vegetation cover, and (6) changing weather conditions. Some methods have been developed to reduce the impact of these problems on analysis, including corrections for tree and riparian vegetation cover e.g. Stephen *et al*. (2010). Remote sensing also has some inherent disadvantages including: (1) the relative cost of obtaining data with sufficiently detailed resolution; (2) temporal replication is often less frequent then required due to the inherent problems in the first point; (3) workers have to be trained or be knowledgeable of specialised software, and (4) the inability to penetrate water (Feurer *et al*., 2008; Marcus and Fonstad, 2008).

3.4.1 Reach scale mapping within the Bere Stream and River Frome

Systematic surveys of the Bere Stream at Snatford Bridge and the River Frome at Frome Vauchurch were undertaken over two annual growth cycles (July 2008-July 2010). From July 2008 to July 2009 both reaches were surveyed on a monthly basis, and every second month from July 2009 to July 2010. Thirty cross-sectional transects were established on both reaches, transects were spaced approximately one metre apart and had corresponding paired transect markers laid on the opposite bank. The transect markers were placed along the whole of the wetted perimeter during bankfull conditions in December 2007. Geographical coordinates of each transect post were referenced in February 2008 using a total station (Nikon).

Surveys recorded temporal and spatial changes in the following: (1) aquatic macrophyte cover; (2) surficial fine sediment depth (m); (3) total water column depth (m); and (4) water flow velocities (m s^{-1}). Survey measurements were taken over the cross-section by placing a taut measuring tape between paired transect poles on either bank. Macrophyte and substrate cover was recorded by marking their extent across the measuring tape, noting the start and end of each macrophyte or substrate (Gurnell *et al.*, 2006).

Measurements of fine sediment depth, total water depth and water flow velocity were taken at 0.5 m intervals across the tape. Total water depth and fine sediment depth were measured using a reinforced metre rule. Total water depth was measured as the depth between the waters' surface and the surface of the gravel bed. Fine sediment depth was calculated by subtracting the depth between the top of the surficial sediment to the waters' surface from the total water depth.

Water flow velocity measurements were made using a flat-sensor type electromagnetic flowmeter (Valeport) on even transect lines starting from transect 0. The water velocity measurement datasets were intended to quantify the flow of water through the reach, and investigate how this was affected spatially by macrophyte cover. A single measurement of water velocity was taken at each designated sampling point within the survey. The head of the sensor was positioned at six-tenths of the water column depth from the waters' surface (0.6D) to measure the mean water velocity at each sampling point (Midgley *et al.*, 1986). The mean water velocity at each point was determined from a 30 second measurement. In all surveys the 'six-tenths depth' rule was used to record a single standard measurement of water flow velocity at each measurement point. This method was deemed more suitable for the survey than multiple measurements (for example at 0.8D and 0.2D), as the majority of points measured were generally <0.5 m in total depth (Gordon *et al.*, 2004).

3.4.2 Plant scale mapping and measurement of *Ranunculus* patches

Three *R. penicillatus subsp. pseudofluitans* (hereafter *Ranunculus*) patches were selected in July 2008 at both study sites for detailed investigation because they were the dominant *Ranunculus* species present. The purpose was to analyse the spatial and temporal changes of fine sediment characteristics and deposition within each of the three plant patches, as well as the corresponding temporal change of plant area and volume. The selection criteria for the patches were that they were representative of the *Ranunculus* plants within the reach, of similar size to one another and healthy in appearance. A mounted quadrat (1.2 m x 0.8 m, Length x Width) similar to that used by

Asaeda *et al*. (2009) (Figure 3.5) was designed and deployed so that the grid (0.1 m^2 mesh) lay above the waters' surface. The intention was to reduce turbulence at the waters' surface and allow for visibility down to the gravel substrate. The poles of the quadrat had little visible impact on flow around the plant (Pers. Obs., G. Davies 2008) and therefore had no influence on plant patch shape or volume because of reconfiguration (O'Hare *et al*., 2007a; Sand-Jensen, 2003).

When the quadrat was *in-situ*, a sketch of the plant patch was made to establish the shape, and estimate the areal cover (m^2). The location of the rooted section of the plant was identified by hand, feeling underneath the plant for the rooted margin and noting where the position fell on the quadrat grid.

Line transects were established across the width of each *Ranunculus* patch. These were spaced evenly with no more than 0.2 m longitudinal spacing between transects from the upstream to the downstream end of each patch. The changing form of each plant patch meant that transects were not fixed within each plant and the number of transects depended on the size of each plant. At least three measurements were made on each transect line across the patches' cross-section. Each measurement point was

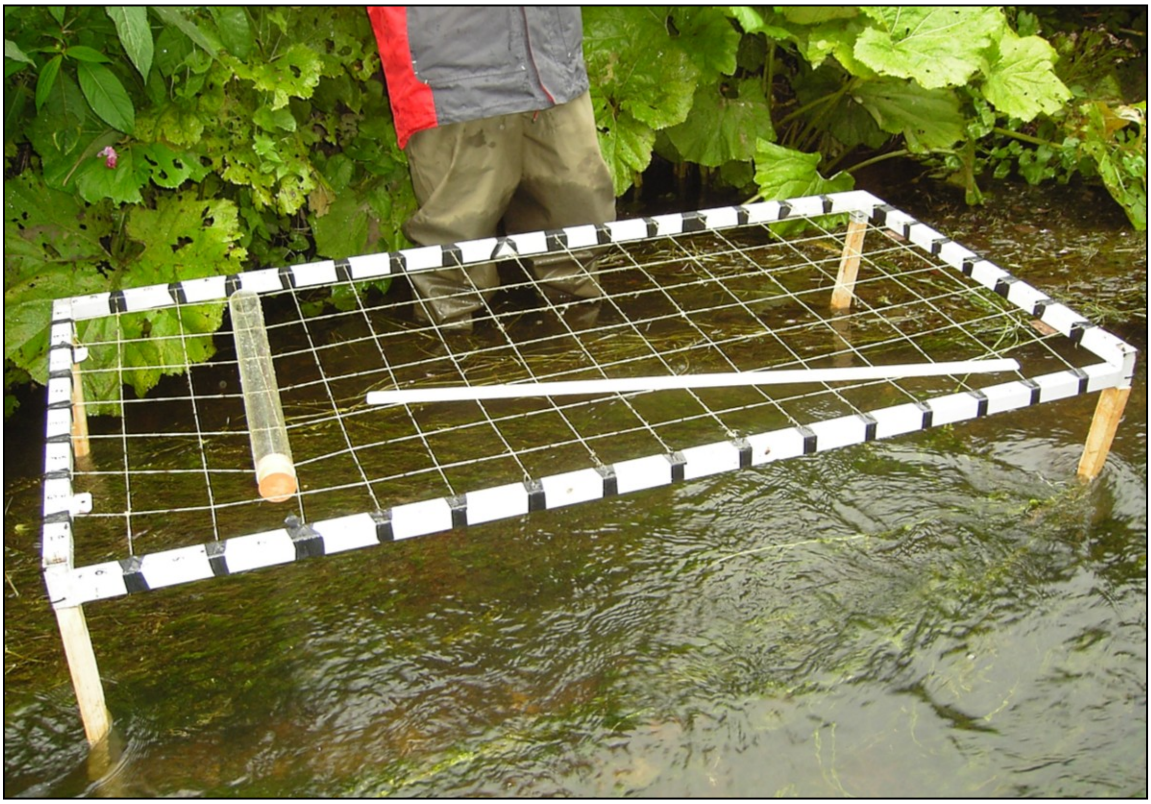


Figure 3.5 – The mounted quadrat used for detailed stand investigations on the Bere Stream and the River Frome. The quadrat is in place on the River Frome in this picture with the study patch beneath during the July 2009 survey. Photograph taken by G. Davies.

referenced to the grid on the quadrat.

A number of measurements were taken within the plant using a reinforced metre rule. The total depth was measured as the depth from the surface of the gravel to the waters' surface. The depth of fine accumulated sediment (sediment depth, m) was measured by noting the depth between the fine sediment surface and the waters' surface and then subtracting this from the total depth.

The uppermost level of the plant patch within the water column at each point is referred to as the vegetated top depth (VTD, m). This was measured as the depth between the waters' surface and the uppermost floating fronds of the plant. An estimate of the depth between the gravel and plant material floating above the gravel at each point is referred to as the vegetated bottom depth (VBD, m). The extent of vegetation at the VBD was determined by hand, placing a palm underneath the plant and gently moving upwards on the metre rule until plant fronds were felt. A measurement of no gap in between the bottom of the plant and the gravel was noted as the point being rooted. There were no instances of un-rooted plant material resting on the bottom of the gravel. An estimate of the proportion of water column depth occupied by plant material at each point is referred to as the vegetated water depth (VWD, m) which was determined by calculating the sum of VTD and VBD, and subtracting this from the total water depth (Figure 3.6).

Plant patches were measured every two months from July 2008 to July 2009, the objective being to capture a year of seasonal growth. This resulted in seven months of measurement for each plant.

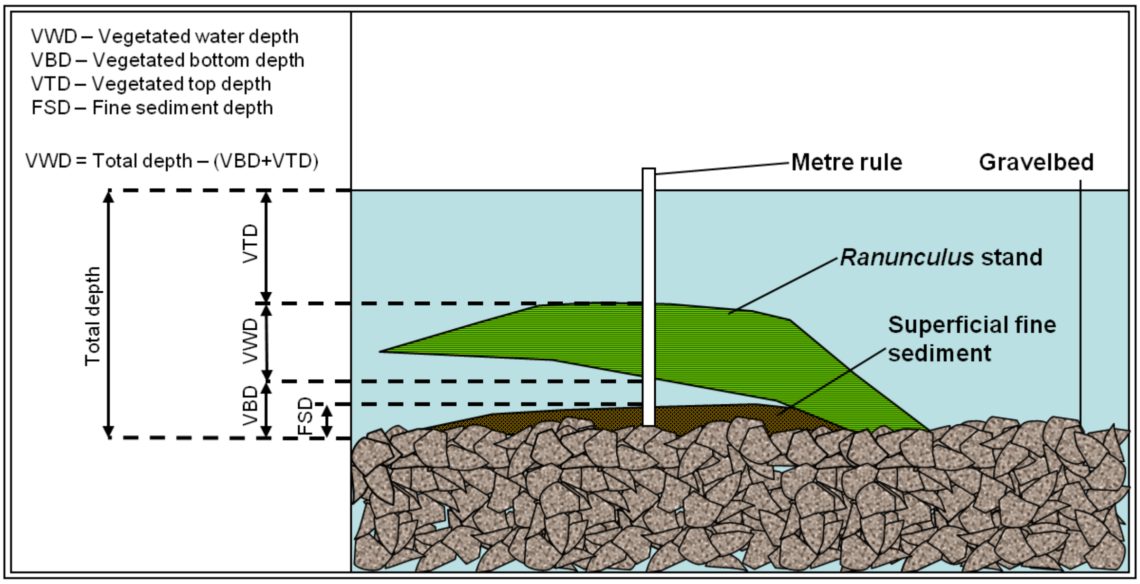
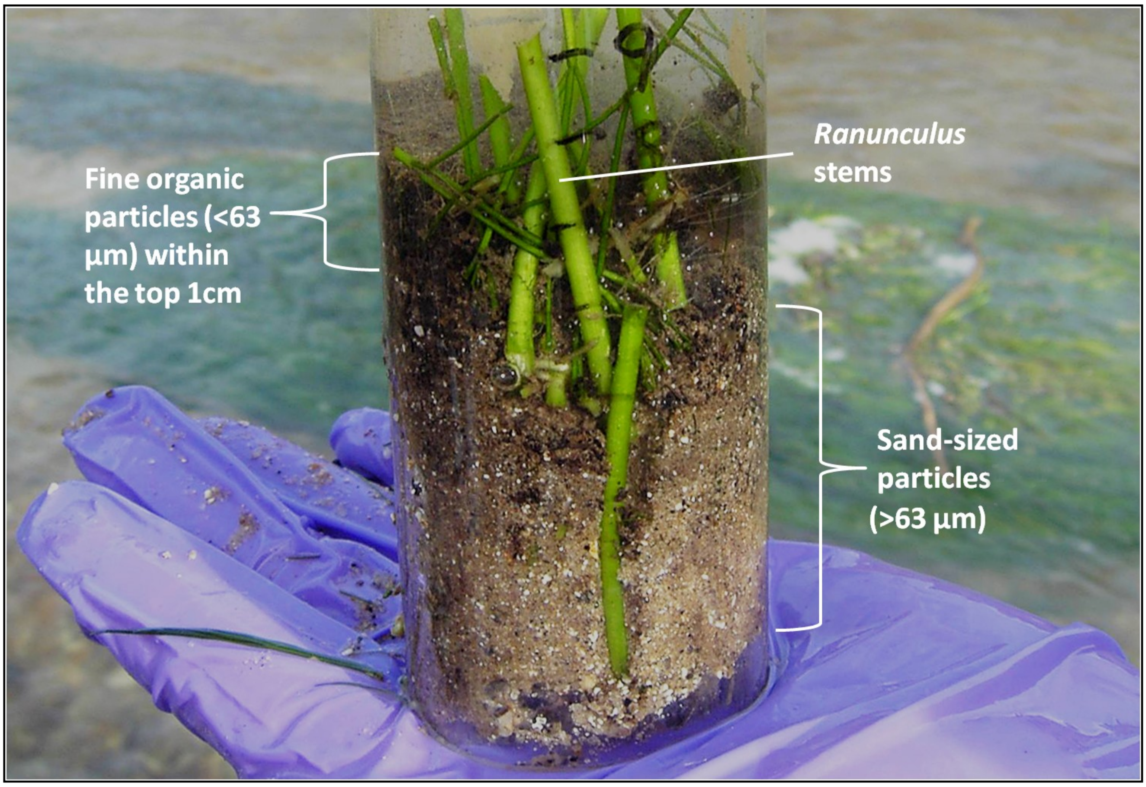


Figure 3.6 – The different measurements of depth made at each point within a single *Ranunculus* patch, all measurements were made to the nearest cm. VWD – Vegetated water depth; VBD – Vegetated bottom depth; VTD – Vegetated top depth, and FSD – Fine sediment depth.

3.5 Deposited and suspended fine sediment sampling

3.5.1 Reach scale fine sediment sampling

Samples of surficial fine sediment were taken every two months from underneath mid-channel *Ranunculus* plants on the Bere Stream at Snatford Bridge and the River Frome at Frome Vauchurch between July 2008 and July 2010. Fifteen sampling points within each reach were selected using randomised coordinates calculated from the reach-scale survey data. One core was extracted from each sampling point using a cylindrical Perspex core tube of 47 mm diameter. Plant material was gently parted to allow coring without exposing fine sediment deposits to the high flow velocities. Retrieved core samples (Figure 3.7) were carefully decanted of excess water and then deposited into grip seal polythene bags, and these were subsequently double-bagged. Samples were then kept chilled until analysis in the lab.



3.5.2 Fine sediment sampling within individual *Ranunculus* patches

Core samples of surficial fine sediment were extracted after each seasonal plant patch survey. Core sites within individual patches were determined using a stratified random approach that targeted five areas of interest within the patches, whilst using the quadrat to reference each cores' position. Figure 3.8 illustrates how the *Ranunculus* patches were partitioned following the guidance of previous workers (Cotton *et al*., 2006; Sand-Jensen and Pedersen, 1999; Sanders, 2006; Watson, 2007). One core was taken from each of the five areas of interest per sampling routine within each plant.

The head area is located within the rooted section of each plant. It is the site that has the greatest initial exposure to higher flow velocities . This zone provides the least protection for surficial fine sediment and has the potential to entrain sediment moving by saltation (Sand-Jensen, 1998). The middle area of the plant is nested within the centre of the rooted section of the patch. It is characterised as having a high cover of plant fronds that create a zone of low flow velocities (Cotton *et al*., 2006; Sand-Jensen,

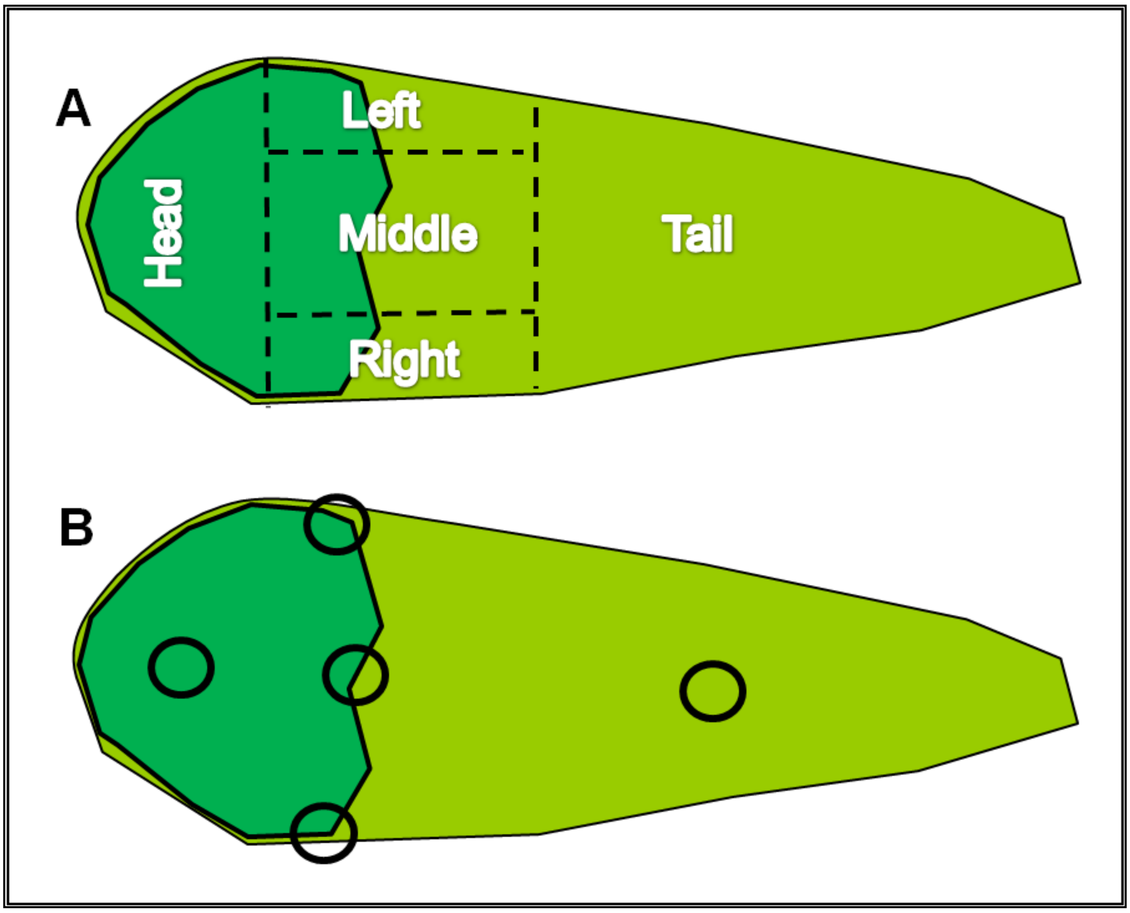


Figure 3.8 – An illustration of an idealised *Ranunculus* patch with the light green representing the total area of the plant, and the dark green representing the area cover of the rooted zone. The top diagram (**A**) illustrates a *Ranunculus* patch that has been arbitrarily dissected into zones of specific interest using guidance from previous workers. The bottom diagram (**B**) with black circles illustrates the possible coring positions within the five different zones.

1998; Wharton *et al*., 2006) which are typically an order of magnitude lower than outside of the patch. It is a potential zone for high levels of fine sediment deposition and retention. The left and right sides of the plant patch are the lateral margins of the rooted section on the respective sides of the plant. Within a symmetrical plant patch they are located either side of the central point of the rooted section. These areas are impacted by high flow velocities (Wharton *et al*., 2006) which lead to active erosive processes creating clear gravel borders, unless they are encroached by other plant patches. The tail area of the patch is outside the rooted zone of the plant. It is characterised as an area of low flow velocities but has unstable sediment deposition due to the loss of plant fronds and disturbance by turbulent eddies caused by the trailing sections of the vegetation (Sand-Jensen, 1998).

Sediment cores were taken using a cylindrical Perspex core tube of 47 mm diameter. Plant material was gently parted so that the corer had access to the fine sediment without any loss occurring from exposure to high flow velocities. Retrieved core samples were carefully decanted of excess water to avoid loss of resuspended fine sediment, and deposited into grip seal polythene bags that were subsequently double-bagged. These were then kept chilled until analysis in the lab.

3.5.3 Suspended sediment sampling

Samples of suspended sediment were retrieved from both field sites during the bimonthly corn pollen releases from January 2009 to July 2010. A portable automatic wastewater sampler (Xian 1000, Bühler Montec) with 24 x 1 l bottle capacity was positioned at the upstream end of each reach (Figure 3.9). The samplers were programmed to collect 0.75 l water samples in hourly intervals for 24 hours commencing at 00:00 before each corn pollen release. The hose of the sampler was positioned in the thalweg of the stream at 0.6 of the depth to ensure standardised sampling protocol. Total equipment failure did not occur during the sampling period, but there were occasional missed samples due to equipment malfunction.

At the end of each sampling programme all sampling bottles were collected, sealed, and kept chilled during transport back to the laboratory. The samples were

Figure 3. 9 – The Xian waste water sampler in position on the Bere Stream in July 2010. Photograph by G. Davies

stored within the laboratory cold store at 8 °C, and were analysed within the 48 hour period after sampling.

3.6 River stage and discharge logging

Stilling wells (Figure 3.10) were installed on each study reach to record changes in river stage, water temperature, and air temperature from February 2009 to July 2010. Each stilling well comprised a vertically mounted drainage pipe housing a hydrostatic pressure transducer (Solinst). Pressure transducers were suspended from a durable non-stretch wire of known length. A barometric pressure transducer (Solinst) was also installed at each site to log changes in local barometric pressure. The loggers were synchronised to record measurements in 15 minute intervals. The actual water stage was determined by subtracting the barometric pressure values from paired the hydrostatic pressure values. Manual depth measurements were taken at both stilling well locations

Figure 3.10 - The location of the stilling well that was installed on the Bere Stream at Snatford Bridge in February 2009. Photograph taken by G. Davies.

with a metre rule during monthly data retrieval to ensure recalculations could be made if the loggers had been affected by sensor drift.

During the study period the hydrostatic loggers at each site had recorded sensor drift which created errors in the measurement of stage. This was noticed from the first dataset which was downloaded on the 22 February 2009. Possible reasons for drift included silt depositing within the logger pipe and lengthening of the wire supporting the logger due to natural wear. As a precaution the sensor pipe housing was cleaned of silt during logger downloads which reduced sensor drift. The manual measurements of depth made with a metre rule during datalogger downloads were used to counteract any further drift by adjusting stage values. Data from hydrostatic and barometric loggers at each site were downloaded in monthly intervals from February 2009 to July 2009, and then every two months from July 2009 to July 2010.

A ratings curve was produced for both study sites to determine the stage-discharge relationship. The measurements of discharge were calculated from reach survey measurements.

3.7 Laboratory analyses and data synthesis for seasonal corn pollen releases

3.7.1 Corn pollen counting

Water samples containing corn pollen were kept chilled after field collection and until analysis in the laboratory. Sediment in samples was removed from water using a 63 μm analytical sieve (Georgian *et al*., 2003) and the volume of water in each sample measured. The resulting suspended particulate matter in the sample was wet sieved onto a gridded Petri dish. The Petri dish was then examined under a dissection microscope and individual corn pollen grains displaying the dye from the most recent release were counted. Throughout the experimental release period there were no naturally deposited un-dyed corn pollen grains found within samples. Counts of corn pollen were expressed as the concentration of corn pollen grains per litre.

3.7.2 Chloride concentration calibration curves & solute transport calculations

Chloride concentration calibration curves (Figure 3.11) were produced in the lab using standards of 5, 10, 20, 50, 100 and 1000 mg $Cl^- l^{-1}$with the same hand-held conductivity probe that was used in field. Readings of conductivity were made at temperatures 5, 10, 15, 20 and 25 °C to encompass the range of possible annual fluctuations in water temperature that may be observed in UK chalk streams (Berrie, 1992).

Nominal Transport Time (NTT) was calculated by constructing Cl^- concentration-time curves, and integrating the area under the curves to determine the time for half of the NaCl solution to pass the downstream station. The difference between the time at which half of the solution was released and the time for half of the solution to pass the downstream sampling station is defined as the NTT (D'Angelo *et al*., 1991; Triska *et al*., 1989). As the NaCl solution was released as a gulp injection the time taken for half of the solution to be released was approximately 0 seconds. Mean velocity of the streamflow was determined by dividing the distance between the downstream and upstream stations by the NTT (D'Angelo *et al*., 1991; Miller and Georgian, 1992; Triska *et al*., 1989).

Discharge was calculated using the following equation (Miller and Georgian, 1992):

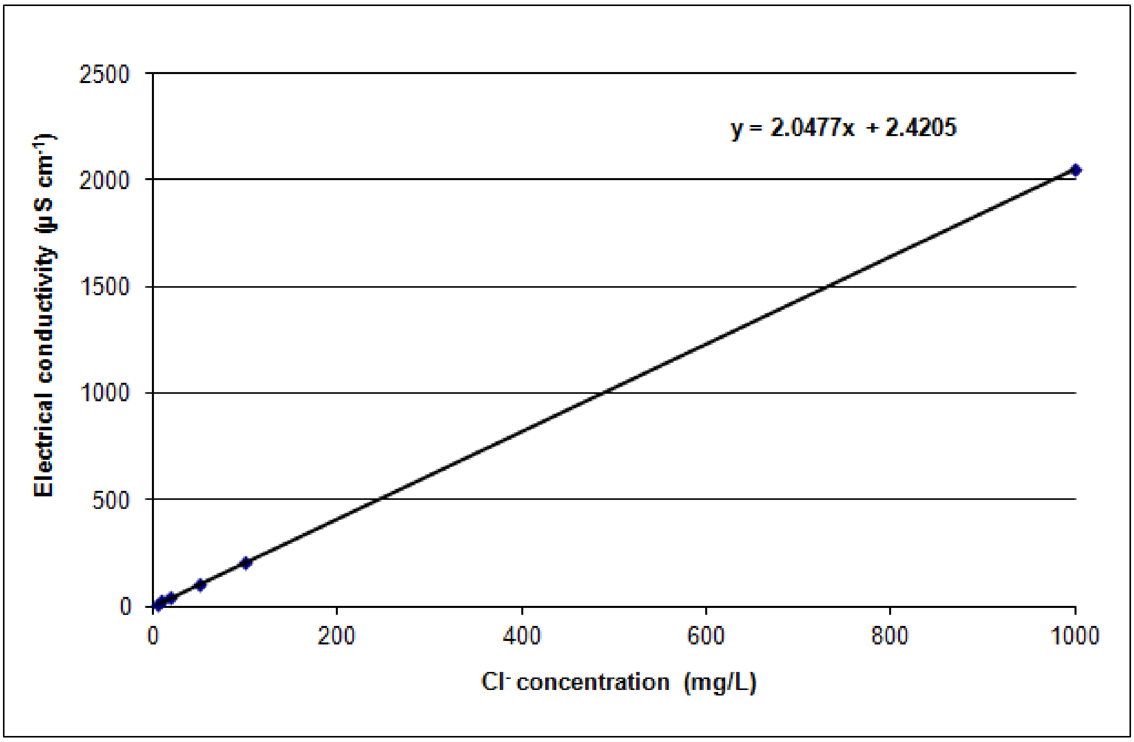


Figure 3.11 – An example of a calibration curve for electrical conductivity and Cl^- concentration of NaCl solution at 10°C.

$$Q = (N/A) \quad [2]$$

where Q is the discharge (l/s^{-1}), N is the mass of NaCl (mg) released and A is the area under the chloride concentration curve (mg Cl^- l^{-1}) over time (seconds).

3.7.3 Estimation of transport efficiency (F_X)

Corn pollen concentration-time curves were constructed resembling that of the Cl^- concentration-time curves. The following equation (Miller and Georgian, 1992) was used to estimate the number of grains in transport passing the downstream station (F_x):

$$F_X = A \times Q \quad [3]$$

where A is the summed area under the curve (number of corn pollen grains l^{-1}) x s and Q is the discharge (l/s^{-1}). This will be referred to hereafter as the transport efficiency or F_X of fine particulate sediment, which is the inverse of the 'retention efficiency' (F_y).

3.7.4 Estimation of retention efficiency (F_Y)

F_Y has been previously described as the "percent of added material retained within the stream" (Webster *et al*., 1987) and was determined using the following equation:

$$F_Y = F_0 - F_X \quad [4]$$

where F_0 is the original number of corn pollen grains released.

3.7.5 Estimation of the longitudinal loss rate (K_p)

The longitudinal loss rate per metre of the stream length (K_P, m^{-1}) was used as an estimate of the rate at which particles fell out of suspension and deposited. K_P is determined by rearranging the following equation (Georgian *et al*., 2003; Minshall *et al*., 2000; Thomas *et al*., 2001):

$$F_y = F_0 \exp(-K_P x) \quad [5]$$

where x is the distance (m) between the upstream and downstream stations.

3.7.6 Estimation of the mean transport distance (S_P)

The mean transport distance (S_p, m) for fine particulate sediment was then determined with S_P as the inverse of K_P. S_P represents an estimate of the mean transport distances that fine particulate sediment will undergo under specific hydrological and geomorphological conditions. This was calculated using the following equation (Georgian *et al*., 2003; Minshall *et al*., 2000; Thomas *et al*., 2001):

$$S_P = 1 / K_P \qquad [6]$$

3.7.7 Estimation of the mean time in suspension (T)

S_P values were then used to calculate the mean time of corn pollen grains in suspension (T, seconds) using the subsequent equation (Wanner and Pusch, 2000):

$$T = S_P / U_W \qquad [7]$$

where U_W is mean water velocity (m s^{-1}).

3.7.8 Estimation of the depositional velocity (V_{dep})

Previous studies have also calculated the depositional velocity (V_{dep}, mm s^{-1}) (Georgian *et al*., 2003; Minshall *et al*., 2000; Newbold *et al*., 2005; Thomas *et al*., 2001) which is the rate at which fine particles leave the water column. This parameter controls for the effects of flow velocity and water depth, which then allows for observations and comparisons of particle deposition rates between streams of differing dimensions (Cushing *et al*., 1993; Georgian *et al*., 2003; Minshall *et al*., 2000; Paul and Hall, 2002). It is a useful parameter to determine the effects of seasonal in-stream vegetation growth on the transport and retention of fine particulate sediment. V_{dep} is determined using the following equation:

$$V_{dep} = K_P\, h\, U_W \qquad [8]$$

where h is the mean water depth (m).

3.8 Reach-scale and plant-scale GIS analyses

The inclusion of geographic information systems (GIS) in mapping has allowed easier transcription, manipulation and presentation of geographical data. Measurements taken in the field at datum can be geo-referenced with a GPS coordinate or EDM relative to datum to improve the accuracy of digital representation. Another important feature of modern GIS desktop packages such as ArcGIS, is the availability of geostatistical methods and models which allow users to predict surface cover of parameters from carefully selected representative points taken in the field (Childs, 2004). Geostatistical models that are commonly used for surface prediction include inverse distance weighting (IDW), polynomial interpolation and kriging. Further detailed discussion on the advantages and limitations of a GIS approach and its application to river channels are reviewed by Downward *et al*. (1994). A number of previous studies on rivers and streams have utilised GIS.

Previous studies on rivers have used GIS as a way of representing datum-collected parameters including ecological, geomorphological and hydrological data to improve management of individual rivers (Hughes and Louw, 2010). The study by Mutz (2000) is a good example of how hydrological and geomorphological data can be collected in a survey and analysed together. Also, the study by Vis *et al*. (2007) demonstrated that it was possible to produce GIS output maps of riverine aquatic macrophytes from remotely sensed data.

A further study on a chalk stream in southern England by Davies and Bass (2006) analysed stream survey data collected in the late 1960s with a GIS to assess changes in water depth, sediment depth and macrophyte abundance. The spatial resolution of the original field data possibly reduced the accuracy of the final output of the produced maps, and their approach demonstrates how spatial resolution of field data is a key factor in any study which includes GIS.

3.8.1 Analysis and synthesis of reach-scale data within the GIS

Reach survey data were analysed using a GIS (ArcGIS v9.2). The total station coordinates of the transect markers were used as georeferences for developing a digitised version of both reaches within a GIS. The output resulted in an array of points that were spatially arranged along transect lines. These points were used as the basis for adding features and data values to the GIS for macrophyte cover, fine sediment depth and total water depth.

Macrophyte cover was determined using an Inverse Distance Weighted (IDW) interpolation of data points from the reach dataset. IDW were chosen as the interpolation method after extensive testing of all of the available modelling interpolations within the ArcGIS package. The output of IDW models gave the most representative and accurate output when predicted surface outputs were compared to the position and values of known points. IDW models use a linear-weighted approach to analyse pre-existing values of sample points to predict unknown values in between known sample points (Childs, 2004). Macrophyte and substrate types were converted into numbers so that the IDW model could produce 2D projections featuring hierarchically coloured filled contours. These projections were subsequently transcribed into vector maps (Figure 3.12).

After producing the vector maps it was possible to further analyse the reach data. This included viewing the spatial arrangement of macrophyte patches and comparing their spatial distribution through different time periods. A quantitative analysis using geostatistical methods was also employed to find the area and volume of surficial fine sediment.

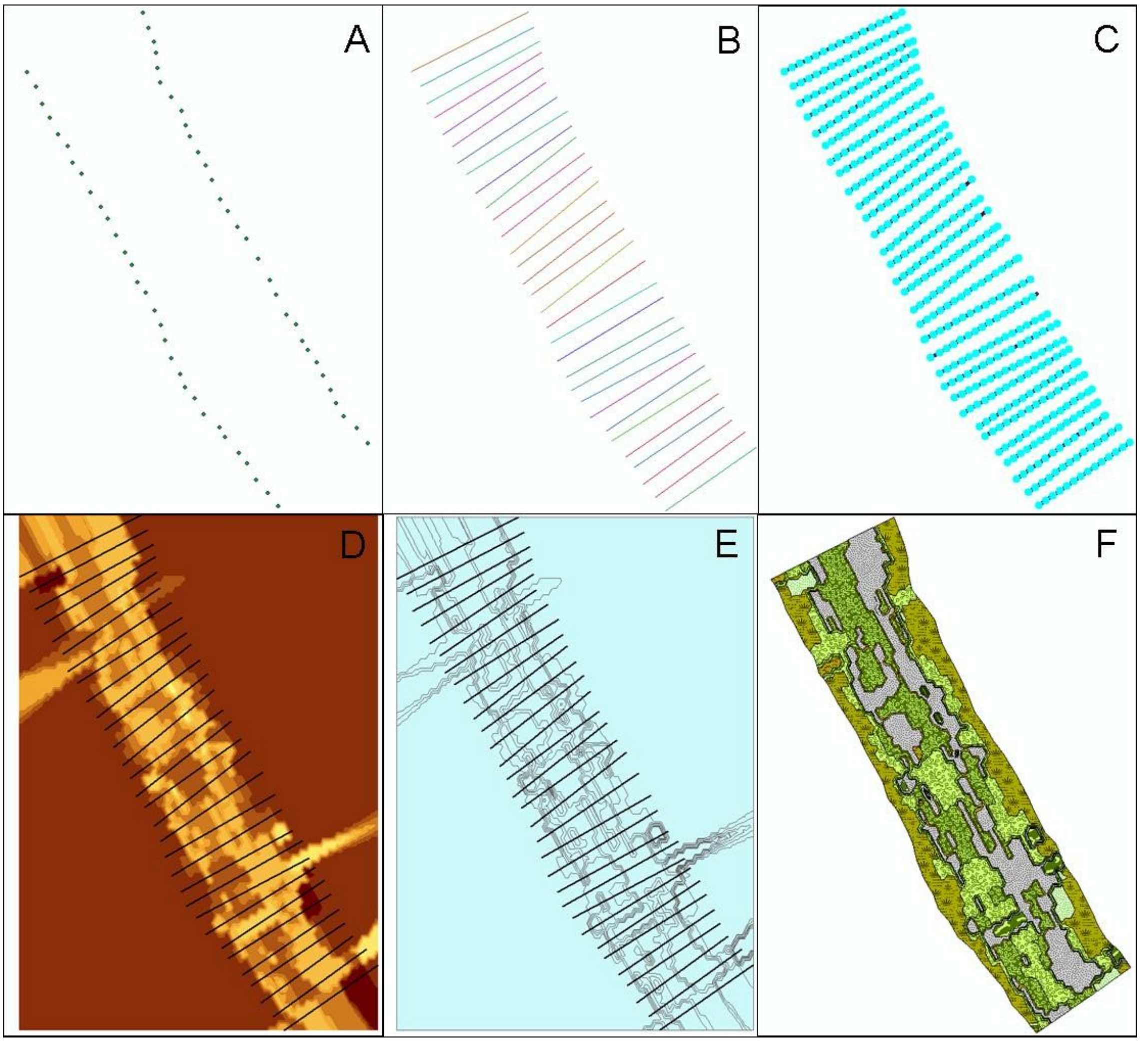


Figure 3.12- The stages of developing a macrophyte map in ArcGIS. (**A**) – Addition of transect post coordinate points; (**B**) – Addition of transect lines on the map; (**C**) – Addition of measurement points; (**D**) – Interpolation of macrophyte/ substrate data using an IDW; (**E**) – Transcription of the IDW into a vector format; and (**F**) – The eventual macrophyte/substrate map.

3.8.2 Analysis of the reach scale area and volume of fine sediment

The depth and area cover of fine sediment at the reach scale was determined with IDW interpolation, using the same method described in section 3.10.1 for macrophyte and substrate cover. The IDW projections for sediment depth were further transcribed into 3D raster grid formats, which allowed for an estimation of the fine sediment volume (m^3) within each reach and underneath specific plant patches. The same resolution was used for all inverse distance weighted interpolations.

Using the GIS it was possible to select and isolate patches of specific species of aquatic macrophyte. Fine sediment depth and cover as well as estimates of sediment volume were analysed underneath patches of *Ranunculus* and *Nasturtium* on the Bere Stream, and underneath *Ranunculus* patches at Frome Vauchurch.

Sediment volumes were combined with values of fine sediment bulk density from reach core samples to produce estimates of the weight of sediment (kg).

3.8.3 Water flow velocity analysis

Water velocity measurements were transcribed as a georeferenced layer of points within the GIS. Individual points were sorted into class ranges in an order of magnitude of velocity ($m\ s^{-1}$), which were ranked in the following order -0.05-0.00, 0.00-0.19, 0.20-0.39, 0.40-0.59, 0.60-0.79, 0.8-0.99, 1.00-1.19, 1.20-1.39 and 1.40-1.99. Each class was assigned an individually coloured triangle symbol within a colour ramp. This allowed flow velocities at each point to be made distinguishable on the GIS output maps.

3.8.4 Analyses of plant-scale data with GIS

A GIS (ArcGIS v. 9.2) was selected as the method for determining the areal cover (m^2), composite plant volume (m^3) of individual plant patches, and volume of underlying fine sediment (m^3) due to the ease and flexibility of data manipulation and range of output (Downward *et al.*, 1994). Composite plant volume is an estimate of the volume occupied by both plant material and interstitial water within vegetated areas.

The scaled field sketches of each plant patch were digitised into a .jpeg file and imported into the GIS. The picture was then resized to the correct scale within the GIS using georeferencing. Following resizing it was possible to determine the areal cover of each plant and its rooted section from each picture.

Vegetated water depth (VWD) and sediment depth data from the field surveys were added into the GIS using point shapefiles. The points were placed in reference to the original point coordinates taken from the survey. Field data of fine sediment depth and VWD was added to corresponding points within the GIS.

Sediment depth data and VWD were interpolated into a 2D filled contour layer using a Local Polynomial Interpolation. Local Polynomial Interpolations were used after thoroughly testing all of the available spatial models to determine which would provide the most accurate output with the type of field data that would be generated. The interpolation output was optimised for accuracy by adjusting the model parameters until the contour distribution approximated to the value of individual sample points of sediment depth and plant cover data. The resulting interpolated layer was then transformed into a raster (3D) layer to estimate the fine sediment volume, and the composite volume of vegetation within each plant patch.

3.9 Laboratory analyses of fine sediment samples

3.9.1 Laboratory analyses of reach scale fine sediment samples

Fine sediment that includes mineral and organic fractions has previously been defined as finer than gravel or <2000 µm (Heppell *et al.*, 2008; Wentworth, 1922; Wharton *et al.*, 2006). But, the upper limit of fine organic matter particle size has previously been recognised as 1000 µm (Georgian *et al.*, 2003; Miller and Georgian, 1992; Vannote *et* *al*., 1980; Webster *et al*., 1999; Webster *et al*., 1987). A consistent and comparable definition of effective (mineral and organic) and absolute (mineral) sediment was required for this investigation. Therefore, it was decided that fine particulate sediment with mineral and organic components were to be represented as <1000 μm akin to other workers on chalk streams (Cotton *et al*., 2006; McConnachie and Petticrew, 2006; Sidle, 1988; Welton, 1980).

Core samples were freeze-dried to remove water from samples. Freeze-drying was used instead of oven drying at 105 °C to prevent further loss or dissociation of organic structures such as flocs within samples (McClymont *et al*., 2007). Freeze drying also prevents the loss of structural water within effective silt and clay samples that can occur at temperatures >105 °C (Rowell, 1994).

Sediment was dry sieved with a 1 mm test sieve (Endecotts) to remove the >1 mm fraction, the sieves were washed with distilled water in between samples. The percentage of sample volume that was >1 mm and <1 mm fraction was determined by weighing the sieved component of both in each sample. Sediment analyses were conducted on the <1 mm fraction of samples. No further analyses were performed on the >1 mm volume from each sample as the focus of the study was on the fine particulate sediment. The <1 mm fraction in each sample was then shaken as thoroughly as possible to produce a heterogeneous mix and sectioned into quarters. Each quarter was analysed using a different laboratory method to determine: (1) organic matter content; (2) bulk density, and (3) particle size distributions of effective and absolute samples

There are a number of methods for determining organic matter content, none of which are able to extract all organic matter from samples (Rowell, 1994). The standard method according to Rowell (1994) is the dichromate method where carbon in the organic matter is oxidised to CO_2 and organic acids. However, the most commonly used methods are those that measure the loss of weight after treatment by ignition at 550 °C or oxidisation with H_2O_2. Organic matter determination was not the focus of this research and so the most cost and time effective method was employed. Loss on ignition was also chosen because of its use by other workers on river sediment analysis (Clarke and Wharton, 2001; Cotton *et al*., 2006; Heppell *et al*., 2008) and at the same field sites (Cotton *et al*., 2006; Heppell *et al*., 2008) which allowed direct comparisons of datasets. Pre-weighed freeze-dried sediment samples were ignited in a muffle oven (Gallenkamp) at 550 °C overnight, then cooled in a dessicator and re-weighed. The loss in weight was used as the organic matter content of the sample (Rowell, 1994).

Measuring the bulk density of river sediment is often difficult because of the unconsolidated nature and high levels of water saturation within samples. This study required a measure of bulk density of the fine particulate sediment, so only the <1 mm sample fractions were used. Bulk density (kg m^3) was determined by weighing a freeze-dried sediment sample and dividing it by the volume that the sample occupied during weighing (Maynard and Curran, 2008).

The particle size distribution of effective and absolute sediment samples was required for analysis in this study. A laser coulter counter (Beckman) was used to analyse the particle size distribution of sediment samples. Maximum pump speeds were used for both effective and absolute samples to ensure sufficient particle suspension and subsequent inclusion of coarse sand fractions (500-1000 μm). Effective sediment samples were analysed for particle size without being sonicated (agitated using ultra-sound) before or during the analysis.

To obtain absolute particle sizes sediment samples were prepared according to Rowell (1994) by digesting the organic component with 20 % hydrogen peroxide (H_2O_2). The particles were then dispersed using sodium hexametaphosphate and anhydrous sodium carbonate (calgon) before analysis (Cotton *et al*., 2006). Sediment samples were sonicated for 30 seconds prior to being added into the laser coulter counter for analysis.

3.9.2 Laboratory analyses of plant scale fine sediment samples

The fine sediment samples retrieved from individual plant patches were analysed for effective and absolute particle size distributions and organic matter as previously described in section 3.9.1.

3.9.3 Laboratory analyses of suspended sediment concentration & rates

Water samples of suspended sediment that were taken using waste water samplers from January 2009 to July 2010 were analysed for mean suspended sediment concentration.

Cellulose nitrate filter papers with a pore size of 0.45 μm (Whatman) were used to separate suspended sediment from the retrieved water samples. Filters were prepared before analysis by oven drying on Petri-dishes at 105 °C for 24 hours. After drying they were transferred to a desiccator chamber and allowed to cool to room temperature before being weighed to six decimal places. Samples were shaken to re-suspend particulate matter and 0.5 l of each sample was subsequently filtered. Filters were then placed in an oven overnight at 105 °C, after which they were allowed to cool in a desiccator chamber before being reweighed.

The estimated rate of mean suspended sediment per second (mg s^{-1}) being delivered to the upstream was estimated by multiplying the mean suspended sediment concentration (mg l^{-1}) by the discharge (l s^{-1}). This was subsequently converted to suspended sediment load per day by multiplying the mean suspended sediment concentration per second by the number of seconds within a day (86400 s). The resulting value of suspended sediment load was converted from mg d^{-1} to kg d^{-1}.

Estimates of mean suspended sediment load being transported through to the end of the reach (mg s^{-1}) was deduced by multiplying the mean suspended load in the upstream with the F_X value from the corn pollen release expressed as a decimal. This was then converted into a value for the suspended sediment load per day using the same method described above for the upstream estimate.

3.9.4 Laboratory analyses of suspended sediment characteristics

A further investigation was made into the sediment characteristics of the suspended sediment at both reaches. Two 20 L water samples were taken on the Frome Vauchurch and Bere Stream reaches at midday on the 23 September 2009, the containers were kept chilled during transport back to London and stored at approximately 8 °C until analysis. Analysis was conducted no more than 48 hours after sampling.

Filtering of suspended sediment was avoided to ensure no material was lost on the filter paper, and to ensure that material from damaged filter papers were not added to samples. Suspended sediment was removed from the water samples by allowing the samples to settle out in 1 L measuring cylinders at 8 °C. On average suspended sediment within samples had settled in no more than 4 hours. Excess water was decanted carefully using a suction hose after the fine sediment in samples had settled, and then a pipette was used to remove the latter remaining water so not to disturb or lose the deposited fine sediment. The resulting water containing the deposited suspended sediment sample was decanted into a clean metal drying bowl, and then placed in an oven overnight at 60 °C. The resulting dry samples were removed from their respective bowls and stored in pre-labelled ziplock plastic bags.

Organic matter content, bulk density and particle size analyses were conducted as described in Section 3.11.1, with the only exception being that the absolute fraction was analysed using the fine sediment that had been ignited in the muffle oven at 550 °C.

3.10 Calculating channel porosity within shallow vegetated stream reaches

Channelised high flow velocities within vegetated streams have been mentioned or described in previous studies relating to channel capacity (Querner, 1997). But there is still little quantitative work on how they are formed and what hydrological, geomorphological and ecological implications they have for the river or stream.

The study of 'leakiness' has been applied to dry savannah habitats which describes how nutrients and resources can be retained or lost by vegetation, with increasing leakiness indicating a increasingly dysfunctional habitat (Ludwig *et al*., 2002). This does not fully apply to the relationship that has been described between aquatic macrophyte growth in streams and rivers and associated changes in flow dynamics. But, the basic concept of nutrients and other resources being transported by aeolian processes, and their subsequent interception by vegetation on a dry savannah plain could be directly contrasted with the transport of water and associated suspended sediment and nutrients between aquatic macrophyte patches. A few studies have sought to describe the lateral momentum conveyance of water in vegetated channels (Helmio, 2004) and channels with bank vegetation (Hirschowitz and James, 2009). But, there are still current gaps in knowledge regarding the development of high flow velocity channels within vegetated rivers as well as their possible uses for habitat management.

The idea of developing an index or measure of channel porosity was a concept that has been developed specifically for this study. Previous work relating to the 3D analysis of high velocity water flowing within a channel has required detailed measurements to be taken in order to produce models e.g. Conveyance Estimation System (HR Wallingford LTD, 2010). The primary driver for channel porosity studies is the possibility of linking the transport capacity or transient storage exchange of water within a channel to associated changes in vegetation volume. Differences in channel porosity are created by the changing seasonal growth of emergent and submergent aquatic macrophyte species.

3.10.1 Data synthesis & GIS analyses for channel porosity

All of the survey datasets between July 2008 and July 2010 on the Bere Stream and Frome Vauchurch sites were used to determine changes in channel porosity. Total water depth measurements were collected during the systematic reach surveys at 0.5 m resolution on each transect cross-section. The resulting measurements from each survey comprised a dataset that was transcribed into a GIS (ArcGIS).

The total depth data were geoprocessed into a 2D spatial layer of filled contours using an Inverse Distance Weighted interpolation. This layer was then converted into a

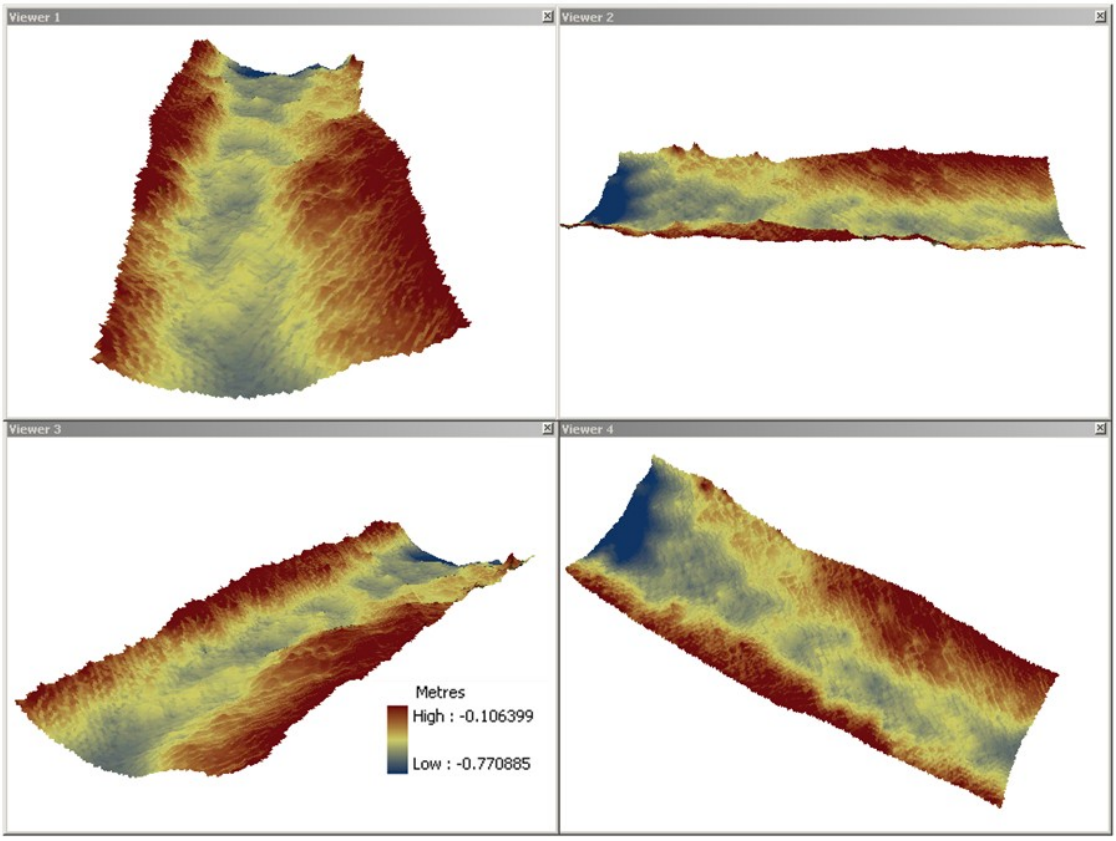


Figure 3.13 – An example of the ArcGIS raster projection output illustrating the 3D representation of total water depth (from the waters' surface) on the reach at Frome Vauchurch on the River Frome from the December 2008 reach survey.

raster file format (3D), and subsequently clipped so that only the part within the boundary of the channel wetted perimeter remained. An estimate of total water volume (m^3) was subsequently calculated for the whole channel reach (Figure 3.13).

Macrophyte areal cover was determined from the monthly macrophyte surveys. This was used to divide the total volume of water into the volume of water that was vegetated and unvegetated. The initial estimate of vegetated volume within reach calculations comprised plant material and the interstitial water within patches. For this reason it was referred to as the composite plant volume. A value of porosity (φ) for each reach survey was then calculated using the following equation:

$$\varphi = V_V / V_T \qquad [9]$$

where V_v is volume of the void space or the unvegetated water volume, and V_T is the total water volume combining unvegetated and vegetated water volumes. Values of channel porosity fall within a scale from 0 to 1. A porosity value of 0 indicates there is no porosity within the reach or it is completely vegetated, and a value of 1 is a reach with no obstruction of flow or a reach completely void of vegetation.

3.10.2 Calculation of *Ranunculus* absolute volume

Absolute plant volume is an estimate of just the plant volume occupying the water column without any interstitial water. The six *Ranunculus* plants that were investigated from July 2008 to July 2009 (See figure 3.8) were harvested immediately after the July 2009 sampling interval. *Ranunculus* plants were removed by manual cutting with secateurs around the base of the rooting zone. The plants were gathered into labelled black bags and kept chilled during transport.

In the laboratory the plants were washed clean of attached sediment and invertebrates, then shaken for one minute to remove excess water (Boeger, 1992). The volume of plant material (hereafter absolute plant volume) within each patch was estimated by volume displacement in water (Novoselov, 1960). Volume displacement was measured by placing all of the plant material into a graduated bucket containing a known volume of water, and noting the difference in volume between water with and without plant material.

A calibration curve was produced for the relationship between absolute plant volume and composite plant volume from the July 2009 data. Using the calibration curve equation it was possible to estimate a back-calculation of absolute *Ranunculus* volume from the composite *Ranunculus* volume estimated by the GIS.

The volume of marginal macrophytes like *Nasturtium* and *Apium* remained the same because their patches were densely vegetated and emergent within all of the reach surveys. Therefore it was assumed that their composite volume was comprised mostly of vegetation, and these were subsequently sufficient for the calculation of channel porosity.

3.10.3 Calculations of emergent and submergent *Ranunculus* volume

The total volume of emergent and submergent *Ranunculus* patches was estimated from reach survey data.Each point within a *Ranunculus* stand was recorded as emergent or submergent. The total number of emergent and submergent *Ranunculus* points within each survey was then counted, and a percentage for each calculated from the total number of measured *Ranunculus* points. The percentage of submergent and emergent *Ranunculus* were multiplied by the total absolute volume of *Ranunculus* to find the estimated absolute *Ranunculus* volume that was submerged and emergent within each survey month.

An adjustment was required for submergent *Ranunculus* patches. In field surveys submergent *Ranunculus* patches were determined as those that were below 0.5 of the total water depth. From this it was apparent that the volume of submerged patches was less than the volume of emergent patches because they occupied less than 50 % of the total water column space compared with emergent *Ranunculus* patches. The value of submerged *Ranunculus* volume was subsequently multiplied by the coefficient value of 0.5 to correct the submergent *Ranunculus* volume.

The total vegetated volume within the reach was then corrected with the new submergent and emergent *Ranunculus* absolute volume estimates.

3.11 Flow resistance and channel roughness within open channels

Flow resistance causes laminar flow to change into turbulent flow within river habitats and other situations where flowing water is present. A fluid with laminar flow is said to be moving in parallel layers past each other at different speeds but in the same direction, and can be described by a linear relationship. In contrast, turbulent flow is where water breaks off from parallel layers into chaotic rough parcels of water that mix with other parcels or packets of water to form eddies and swirls (McNair *et al*., 1997). Turbulent flow can only be described statistically using averages, it is a forefront topic of research that depends on experimentation and mathematical modelling (Gordon *et al*., 2004).

Flow resistance is also caused by grain or surface resistance. Grain resistance is the resistance within a channel bed caused by individual grains and is therefore important within coarse substratum rivers and streams. Form resistance is more associated with the topography of the channel bed, with channel bedforms being the result of interactions between the streamflow and bed sediments.

The quantification of laminar flow and flow resistance is reliant on the viscosity of fluid, with increased viscosity dampening turbulent flow. The resistance of an object or fluid to acceleration or deceleration can be described with a measure of inertia, with high inertial forces promoting turbulence (Vogel, 1994). The ratio of inertial forces to viscous forces governs whether flow is either turbulent or laminar (Gordon *et al*., 2004).

3.11.1 Reynolds number

The Reynolds equation (Re) was developed by Osborne Reynolds to describe whether flow in a channel or pipe is either laminar or turbulent using dimensionless values. The Reynolds equation is derived as:

$$\mathrm{Re} = \frac{VL\rho}{\mu} \qquad [10]$$

where V is velocity (m/s), L or characteristic length (m) in stream channels is the hydraulic radius, ρ is fluid density (kg/m^3) and μ is dynamic viscosity ($N \cdot s/m^2$). Laminar flow in open channels is generally maintained until Re values of 500 (Shaw, 1994), although values can exist on a transitional scale from 500 to 2000 in open channels

(Chow, 1959). The Re value that causes the transition in between laminar flow and turbulent flow is known as the critical Re value or critical Reynolds number, this is normally given as 500,000 (Gordon *et al.*, 2004).

3.11.2 Chezy-Manning equation or Manning's n equation

The Chezy-Manning's equation (hereafter Manning's n) was developed by Robert Manning from an earlier equation devised by Antoine Chezy. The equation is used to generate dimensionless values that can be used to describe channel flow within uniform channels open channels. The Manning's n equation is derived by the rearrangement of the following equation:

$$Q = \frac{1}{n} A R^{\frac{2}{3}} S^{\frac{1}{2}} \qquad [11]$$

where Q is discharge (m^3/s), S is slope of the energy line, R is the hydraulic radius (m), and n is the Manning's n coefficient.

Methods of devising Manning's n estimates have now been developed for non-uniform rivers. Cowan (1956) was the first to produce estimates of Manning's n values for small streams with natural channels using 'flow retarding factors'. Since Cowan (1956) there have also been other authors who have attempted to improve estimates of Manning's n values within natural channels using computations of known values of discharge, channel geometry and water level data *c.f.* Chow, (1959) and Jarrett, (1985).

Within this research estimates of the Manning's n value for each survey month at both sites were estimated using data from the most upstream and unvegetated cross-section.

3.12 Data analyses

Statistical analyses were performed on a number of the datasets generated for the three research aims using Minitab (v. 12). The determination, justification and use of particular statistical methods are discussed within the results sections of each chapter.

CHAPTER 4

The influence of seasonally-changing macrophyte cover on fine sediment deposition and storage at the reach scale

4.0 Introduction

The first part of this chapter (section 4.1) describes the results relating to changes in fine sediment depth, sediment characteristics and volume at the reach scale in relation to seasonally-changing macrophyte cover. Data from both the Bere Stream at Snatford Bridge and Frome Vauchurch on the River Frome were used as part of the two stream analysis. Following this is the discussion of the main findings from the results in section 4.2.

4.1 Results

4.1.1 Changes in macrophyte cover on the Bere Stream, July 2008 – July 2010

Total macrophyte cover (Figure 4.1) was dominated by the growth and recession of two aquatic macrophytes. *Ranunculus* (comprising *R. penicillatus* subsp. *calcareous* and *R. penicillatus* subsp. *pseudofluitans*) and *Nasturtium officinale* (hereafter as *Nasturtium*). During the summer months marginal aquatic macrophytes were represented by considerable growths of *Apium nodiflorum* (hereafter as *Apium*) and other macrophyte species such as *Oenanthe* sp. and *Urtica dioica*.

The first peak of total macrophyte cover occurred in September 2008 (75 %). This was mainly attributed to the dominance of *Nasturtium* from August 2008 through to February 2008. *Nasturtium* area cover (hereafter *Nasturtium* cover) steadily decreased from peak cover of 55 % in September 2008, to its lowest cover of 3 % in April 2009. The peak cover during the September 2008 survey also coincided with one of the lowest values of channel discharge at 0.05 $m^3 s^{-1}$.

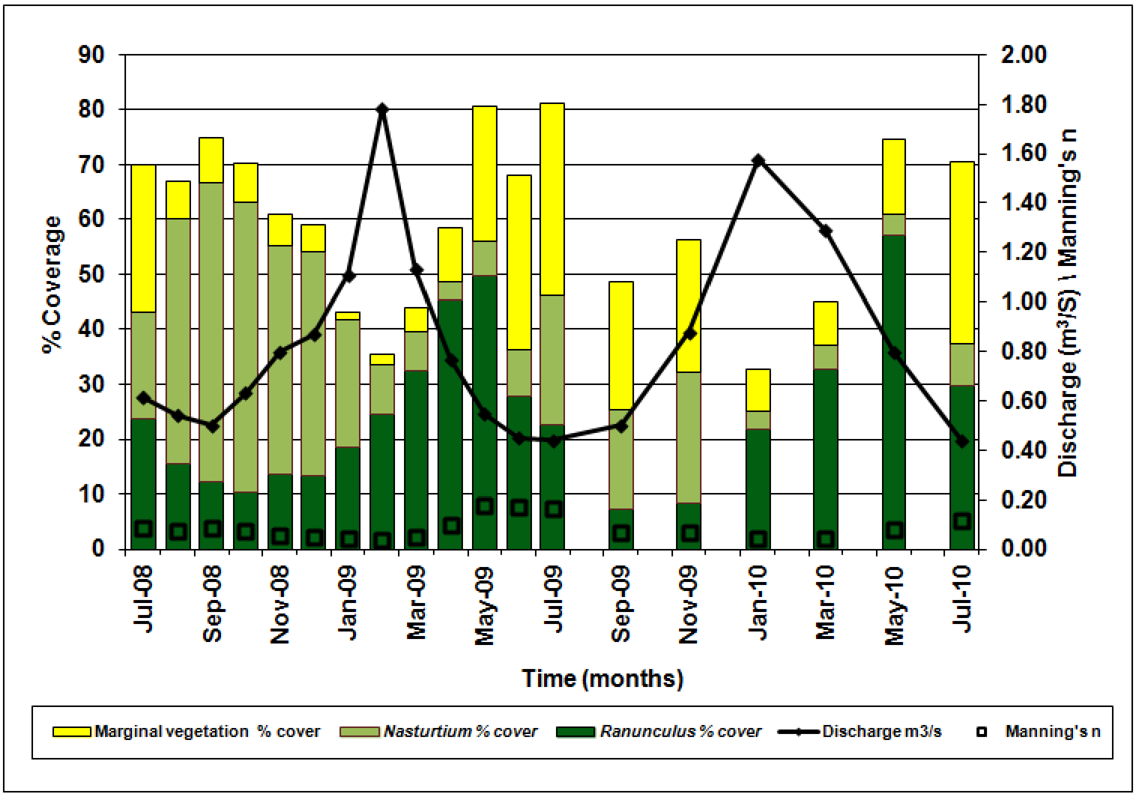


Figure 4.1 – The changes in % cover of *Ranunculus*, *Nasturtium* and marginal macrophytes primarily composed of *Apium* as well as discharge (m^3 /s) and values of Manning's N on the Bere Stream at Snatford Bridge, Dorset from July 2008 to July 2010.

The lowest total macrophyte cover between July 2008 and July 2009 occurred during the winter period in February 2009 (35 %), which coincided with the lowest value of Manning's n for the channel at 0.03 and a marked increase in discharge of 1.70 m^3 s^{-1}. During this period *Nasturtium* cover had rapidly decreased and the areal cover of *Ranunculus* had steadily increased from December 2008, making it the dominant macrophyte from February 2008 through to May 2009, with peak cover of *Ranunculus* at 49 % in May 2009. In the summer of 2009 there were two peaks in vegetation cover in May 2009 and July 2009 which both equalled 81 %.

The peak in vegetation cover during May 2009 occurred due to the rapid increase in the cover of other macrophyte species comprising mostly of *Apium,* from 10 % in April to 25 % in May 2009. Corresponding with this change was the greatest value observed for channel roughness (Manning's n value of 0.18) and a low seasonal value of channel discharge at 0.55 m^3 s^{-1}.

The peak in total macrophyte cover during July 2009 comprised of *Ranunculus* cover at 22 %, a peak in the growth of *Nasturtium* at 24 % and a peak in the cover of other macrophyte species at 35 %. Corresponding with this increase in total macrophyte cover was the lowest value of channel discharge (0.44 $m^3 s^{-1}$) and a considerably high value of channel roughness represented by Manning's n (0.16).

From July 2009 to January 2010 there was an overall decline in total macrophyte cover to 33 %. During this period the areal cover of the main macrophyte species changed considerably. In addition, a steady increase in values of channel discharge occurred with a discernable peak in January 2010 of 1.58 $m^3 s^{-1}$, while at the same time channel roughness represented by values of Manning's n steadily decreased to 0.04 in January 2010. There was an initial increase of *Nasturtium* and *Apium* in November 2009 to 24 % each, followed by a sharp decrease in the area cover of both plants to 3 and 8 % respectively in January 2010. *Ranunculus* area cover had increased to 22 % in January 2010, which made it the dominant macrophyte within the reach at that time.

Between January 2010 and May 2010 vegetation cover increased considerably peaking at 74 % in May 2010. Subsequently total macrophyte cover started to decrease from May 2010, with cover estimated as 71 % in July 2010. The pattern of total macrophyte cover comprised mostly of the increasing cover of *Ranunculus* from January 2010 to its peak cover of 57 % in May 2010. From March 2010 *Nasturtium* cover had started to increase in cover to 33 % in July 2010. In the meanwhile values of channel discharge decreased sequentially from the peak in January 2010 to a noticeably low value of 0.44 $m^3 s^{-1}$ in July 2010. During the same time period channel roughness gradually increased to 0.12 in July 2010.

4.1.2 Spatial distribution of macrophytes within the Bere Stream, July 2008 – July 2010

The distribution of macrophytes within the reach between July 2008 and July 2009 is illustrated by reach-scale maps produced by GIS (Figure 4.2), and allows a more detailed consideration of changing macrophyte assemblages.

In July 2008 discrete *Ranunculus* patches were emergent and constricted to the central run of the channel. The encroachment of *Nasturtium* began with patches forming in the margins amongst *Oenanthe* sp. and *Urtica dioica*. *Nasturtium* had also developed within the centre of the stream channel on top of *Ranunculus* patches. The sporadic distribution of the macrophyte patches caused smaller channels of higher velocity flow to form separately from the thalweg in between patches.

In the succeeding months to December 2008 *Nasturtium* completely dominated the channel margins and had started to grow in towards the centre of the channel. In some instances, the growth of *Nasturtium* had constricted the width of the channel to 1-2 m, resulting in a concentrated and centralised path containing high water flow velocities. As a result, *Ranunculus* abundance had decreased into smaller and fragmented patches that were sparsely distributed within the centre of the channel. Patches of *Apium* were present throughout but confined to the inner most margins of the stream.

From January 2009 *Ranunculus* patches had started to re-establish within the centre of the channel, forming a long strip of continuous patches. From January to April 2009 *Ranunculus* patches were emergent, and between February and March 2009 a mosaic of individual but inter-connected patches had developed from the centre of the stream channel. In between the surveys of March 2009 and April 2009, the emergent *Ranunculus* had split the main channel into two. The stream flow was constricted between *Ranunculus* patches in the centre and *Oenanthe* growing from the channel margins.

In May 2009 channel flow was choked by *Ranunculus* growing in the centre of the channel, also *Apium* that had started to encroach from the margins into the channel flow. From May to July 2009 *Apium* continued to expand its growth into the centre of the channel, much like the growth of *Nasturtium* in the summer to autumn period of 2008. This subsequently constricted the stream flow into the centre of the channel. *Nasturtium* had also begun to encroach on top of *Ranunculus* patches in the centre of the channel and also within the *Apium* patches in the margins.

From July to September 2009 the cover of *Ranunculus* patches dominating the centre of the channel had decreased dramatically to just 7 %. *Nasturtium* and marginal macrophytes (comprised mainly of *Apium*) had also decreased, to 18 and 23 % respectively. *Nasturtium* remained dominant within the left bank margins in the upstream part of the reach. *Ranunculus* cover appeared to be similar between the September 2009 and November 2009 survey, from 7 to 8 % correspondingly. The increase in the total macrophyte cover between September and November 2009 was mainly due to an increase in *Nasturtium*, which had increased its dominance within the left bank marginal zone.

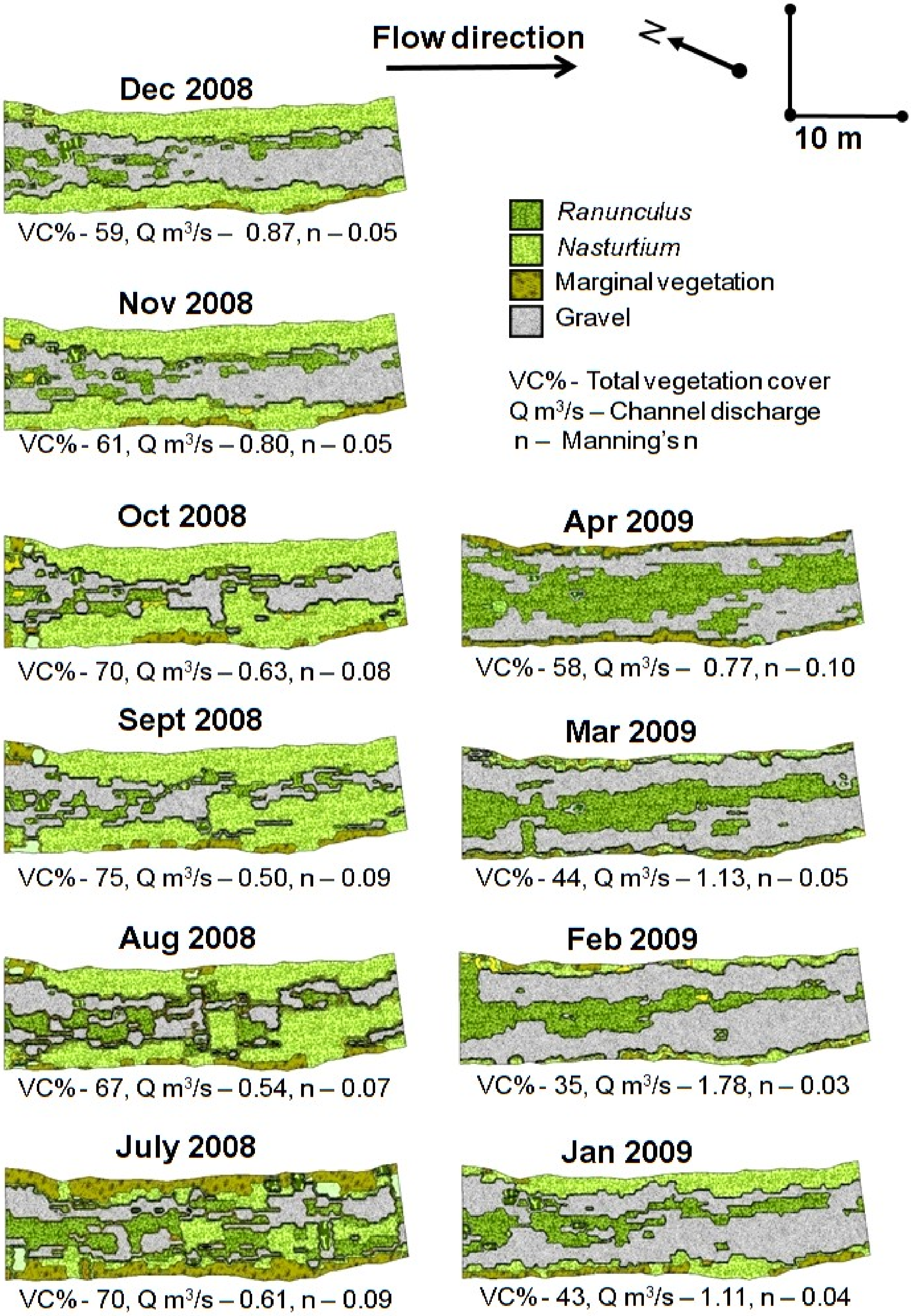


Figure 4.2 - Maps produced from the GIS illustrating the spatial and temporal changes of vegetation and bare gravel within the Bere Stream at Snatford Bridge from July 2008 to July 2010. Values of total vegetation cover (VC%), channel discharge (Q) and Manning's n accompany the map of each month.

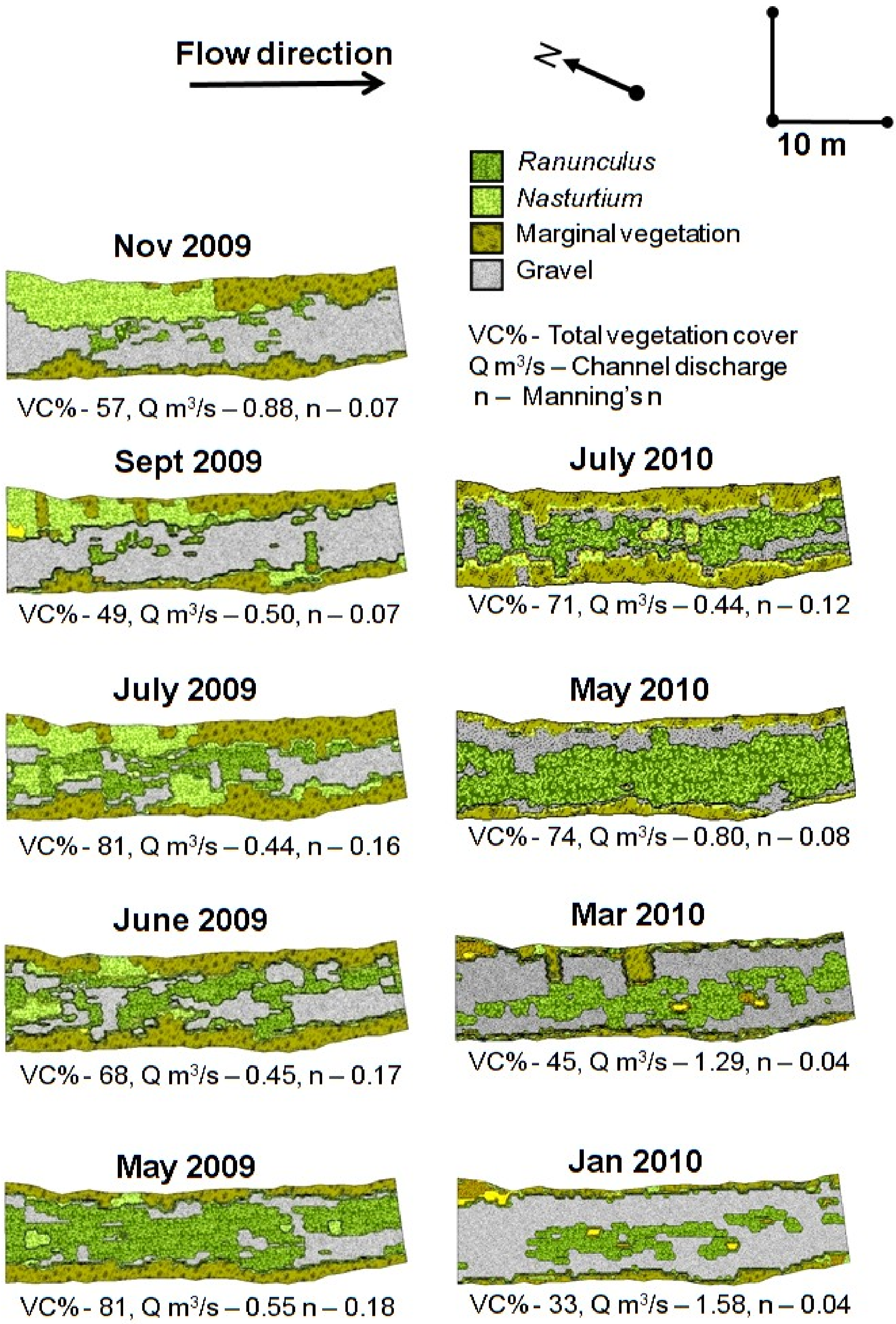


Figure 4.2 continued.

From November 2009 to January 2010 there was a noticeable loss of both *Nasturtium* and marginal macrophytes from the reach which was visible in the total macrophyte cover values. From January to March 2010 *Ranunculus* was arranged within the centre of the channel. *Ranunculus* plants were growing in longer and thinner discrete patches in January 2010. These few plants then became wider patches that were increasingly interconnected until they almost filled the centre of the channel by May 2010. *Nasturtium* was very much restricted to the margins of the channel in small isolated patches amongst a majority of *Apium*. From January to May 2010 *Nasturtium* did not increase in cover to a great extent, with the growth of *Nasturtium* being restricted by increasing dominance of *Apium* within the channel and larger overhanging growth of *Oenanthe* sp. lining the riparian wetted perimeter.

Ranunculus still dominated the centre of the channel in July 2010, but larger plants had started to fragment and transform into smaller patches. Large growths of *Apium* had encroached from the margins into the channel, which had led to the flow of water becoming more constricted into the centre of the channel. *Nasturtium* was present in small thinly distributed patches on the outside of the marginal areas of *Apium*. *Nasturtium* had also started growing in the centre of the channel by emerging in the centre of *Ranunculus* patches.

4.1.3 Changes in macrophyte cover at Frome Vauchurch, July 2008 –July 2010

Total macrophyte cover was dominated by *R. penicillatus* subsp. *pseudofluitans* (hereafter referred to as *Ranunculus*) throughout the whole annual cycle (Figure 4.3). The reach at Frome Vauchurch was species-poor in comparison with the Bere Stream. There were no aquatic macrophytes or aquatic terrestrial plants that dominated the margins of the reach.

The cover of marginal riparian vegetation did not have much influence within the reach even though it was seen to encroach into the centre of the channel, and directly competed with *Ranunculus* in those areas. In the spring and summer months of 2008, 2009 and 2010 the right bank was dominated by substantial growths of *Petasites vulgaris* and *Oenanthe* sp. These subsequently died back which allowed *Urtica dioica* to become the dominant marginal species. The left bank was co- dominated by *Urtica*

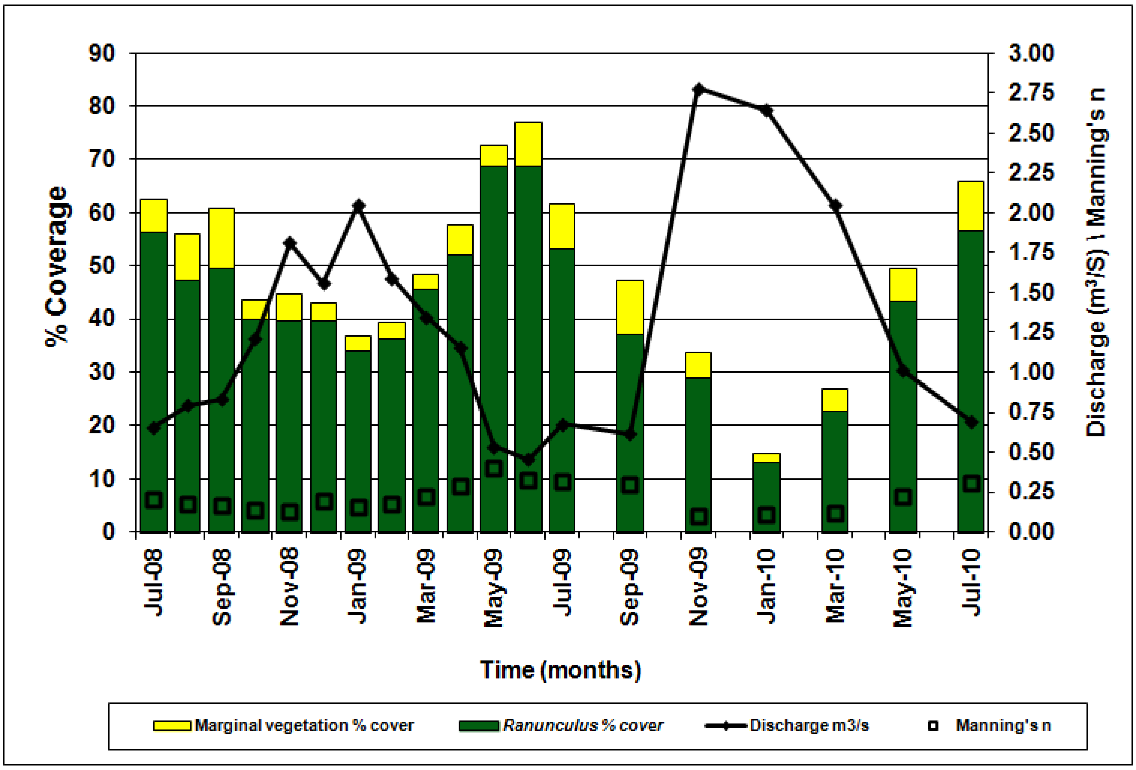


Figure 4.3 – The changes in % cover of *Ranunculus* and marginal vegetation as well as discharge (m^3 /s) and values of Manning's N on the River Frome at Frome Vauchurch, Dorset between July 2008 and July 2010.

dioica and *Rubus fruticosus* bushes, these plants commonly intruded into the flowing water in the summer months. The peaks in marginal riparian vegetation cover occurred in September 2008 and September 2009, at 11 and 10 % correspondingly. The cover of marginal vegetation never fell below 2 % throughout the two year survey period, with January 2010 possessing the least cover marginal vegetation. This coincided with a large seasonal peak in channel discharge 2.64 m^3 s^{-1} and a considerable decrease in channel roughness or Manning's n to 0.11.

Seasonal variations in total vegetation cover at Frome Vauchurch were determined by corresponding changes in *Ranunculus* cover. The seasonal growth and recession of *Ranunculus* followed a pattern similar to that of the Bere Stream with high percentage cover in the summer months with peaks in cover in the July 2008, May 2009 and June 2009 survey months at 56, 69 and 69 % respectively. These were associated with low values of channel discharge (0.54, 0.46 and 0.68 $m^3 s^{-1}$ correspondingly) and high values of channel roughness as demonstrated by Manning's n values, between 0.40 and 0.32.

A steady decrease in total within channel vegetation cover occurred from September 2008 through to January 2009 due to seasonal dieback related to increases in channel discharge. January 2009 possessed the lowest cover of *Ranunculus* during the first annual cycle at 34 %, which also coincided with a peak in channel discharge at 2.1 $m^3 s^{-1}$. The cover of *Ranunculus* increased gradually through the spring months reaching its peak cover in May and June 2009, and subsequently decreasing in cover to 53 % in July 2009. This coincided with decreases in marginal vegetation and was also associated increases in channel roughness, represented by Manning's n values.

Ranunculus cover continued to decrease steadily to 13 % (in January 2010). The decrease in *Ranunculus* cover was associated with increases in channel discharge, peaking in November at 2.78 $m^3 s^{-1}$. There was a sustained growth of *Ranunculus* through to July 2010, with *Ranunculus* cover almost doubling between March and May 2010 with an increase of 20 %. Marginal vegetation cover also increased gradually from 2 to 9 % from January to July 2010 correspondingly. The growth in coverage during these months was most likely due to seasonal decreases in channel discharge 2.64 $m^3 s^{-1}$ in January 2010 to 0.69 $m^3 s^{-1}$. The reduced channel discharge and increased vegetation cover within the reach resulted in increased channel roughness, with Manning's n values increasing to 0.31 in July 2011.

4.1.4 Spatial distribution of macrophytes within Frome Vauchurch, July 2008 – July 2010

The GIS-generated maps summarise the spatial changes of *Ranunculus* abundance and distribution within the stream channel over annual cycles of growth (Figure 4.4).

The *Ranunculus* patches were orientated in the direction of the flow within the channel, with the main flow running from the centre of the channel to the direction of the downstream right bank. In July 2008 *Ranunculus* was separated into two main masses, with a main strip of clear gravel substrate dividing the two. This strip also represented the position of the thalweg within the stream channel.

Surficial fine sediment was present within the most upstream part of the reach in front of the *Ranunculus* patches from July to August 2008. The covering of fine sediment on the gravel had receded by October 2008, after which there was only gravel in the upstream part of the reach. A deep accumulation of fine sediment was located next to the left bank in the most upstream section of the reach. This was present throughout the entire two year survey period.

From July 2008 to February 2009 *Ranunculus* patches gradually fragmented into a larger number of smaller patches scattered throughout the reach, with increasingly wider strips of bare gravel forming in between patches over time. Throughout the spring and summer months *Ranunculus* growth gently increased to a peak in *Ranunculus* cover in May and June 2009. During this point the passage of water flowing through the reach was highly obstructed by abundant *Ranunculus* growth, which caused many 'pseudo-channels' of high velocity water to be formed within the vegetated mass in the centre of the channel. In July 2009 *Ranunculus* cover started to decline and individual patches became more abundant.

From July 2009 to January 2010 *Ranunculus* patches were much smaller than the previous year but remained interconnected within the centre of the channel. The majority of the *Ranunculus* cover was lost in between the September and November 2009 surveys (Figure 4.4). Further losses of cover resulted in the least abundance of *Ranunculus* during the two year survey period in the January 2010 survey. From January 2010 *Ranunculus* patches again became larger. *Ranunculus* had grown into one large mass in the centre of the channel with 'pseudo-channels' of high velocity flow being formed within the central mass of vegetation occurring between the March and May 2010 surveys in May and July 2010.

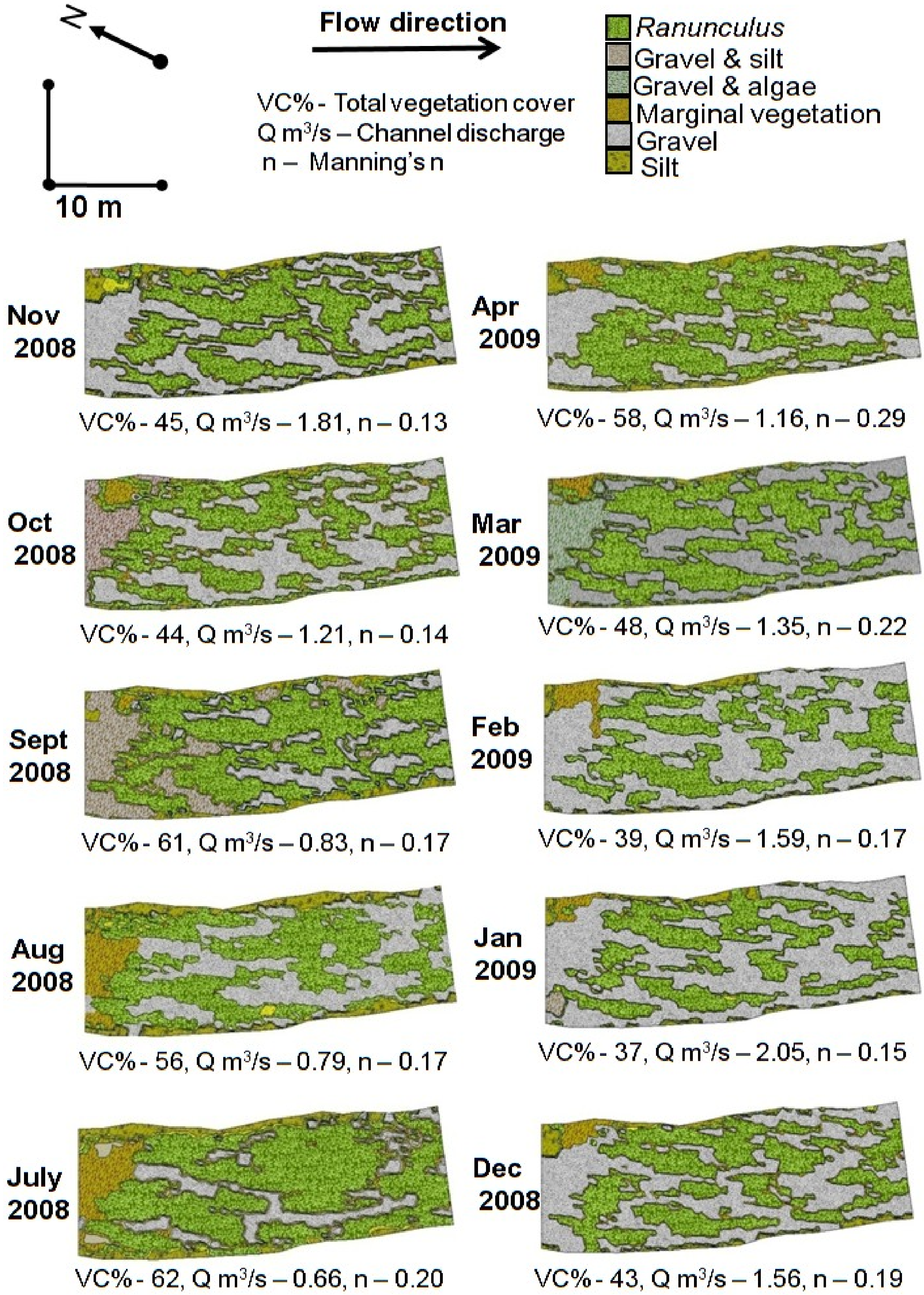


Figure 4.4 Maps produced from the GIS illustrating the spatial and temporal changes of vegetation and bare gravel within the River Frome at Frome Vauchurch from July 2008 to July 2010. Values of total vegetation cover (VC%), channel discharge (Q) and Manning's n accompany the map of each month.

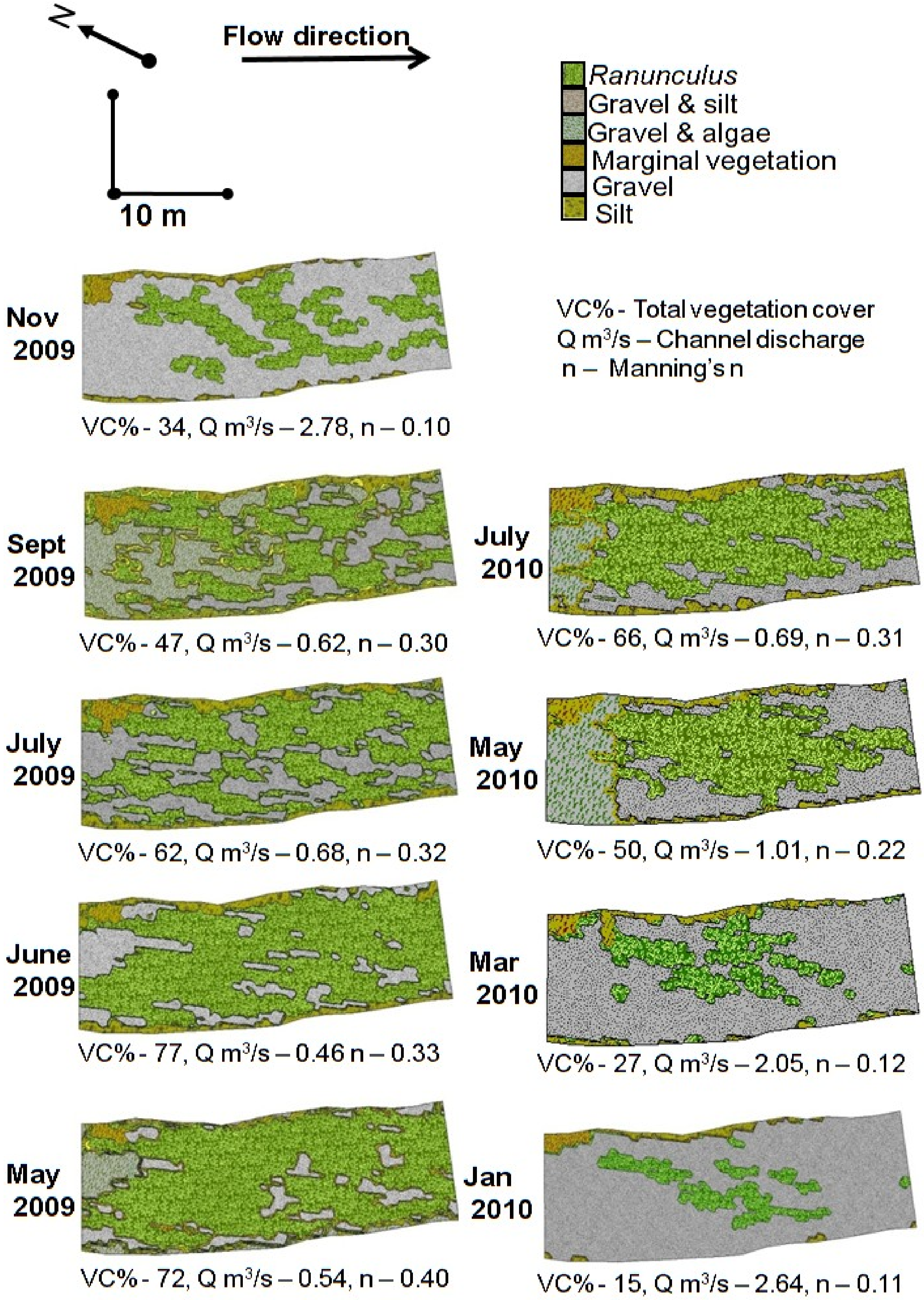


Figure 4.4 continued.

4.1.5 Reach scale characteristics of surficial fine sediment deposits

Samples of fine sediment were taken from within *Ranunculus* stands on both study reaches every two months during the survey period between July 2008 and July 2010. Sediment samples were analysed to determine the effective and absolute particle size, spatial distribution, organic matter content and bulk density. Median particle size (hereafter D_{50}) values are one of the main variables within sediment samples used to describe the characteristics of a particle size distribution within a sample (Golterman, 1983; Gordon *et al*., 2004). The % volume of silt and clay within samples was also of interest, as this is the most important sediment fraction in terms of contaminant binding and transport (Armitage *et al*., 2008; Heppell *et al*., 2009; Walling *et al*., 2006).

4.1.5.1 Seasonal changes in D_{50} values of effective particle size from the Bere Stream

Particle D_{50} values of the effective fraction were determined from sediment samples retrieved from the Bere Stream between July 2008 and July 2010 (Figure 4.5).

There appeared to be a seasonal variability in the D_{50} values of the effective particle size. Sediment samples from July 2008 had the greatest mean D_{50} value (448 ± 185 (SD) µm), and also the greatest sample range (145 to 676 µm). From September 2008 to July 2010 mean D_{50} values remained within the medium sand grade between 275 and 348 µm. The sample was confined within the fine to coarse sand range from 159 to 552 µm. Samples from May 2010 had the smallest mean D_{50} values (199 ± 98 (SD) µm), and September 2009 had the smallest sample range of all the sampled months between 231 and 365 µm.

Statistical analyses were performed on the effective particle D_{50} dataset, to test for significant differences between sample months. Effective particle D_{50} datasets from each month were treated as non-parametric because they were comprised of median values. A Friedman statistical test determined that there was a highly significant difference (*d.f.* 12, $\boldsymbol{P} = 0.001$) between all sample months for values of particle D_{50}. A series of *post-hoc* Mann-Whitney U-tests with Bonferonni Correction (alpha value = 0.0006) were used to compare all months against each other for differences in effective median particle size because the result of the initial test was significant (Dytham, 2003) (Figure 4.5).

The values of particle D_{50} within effective sediment samples of the May 2010 sample month were found to be significantly different to samples taken during the following sample months July 2008, November 2008, January 2009, March 2009, July 2009 and September 2009. This suggests that the D_{50} values of effective particle sizes in May 2010 was significantly lower in comparison to those of some other months.

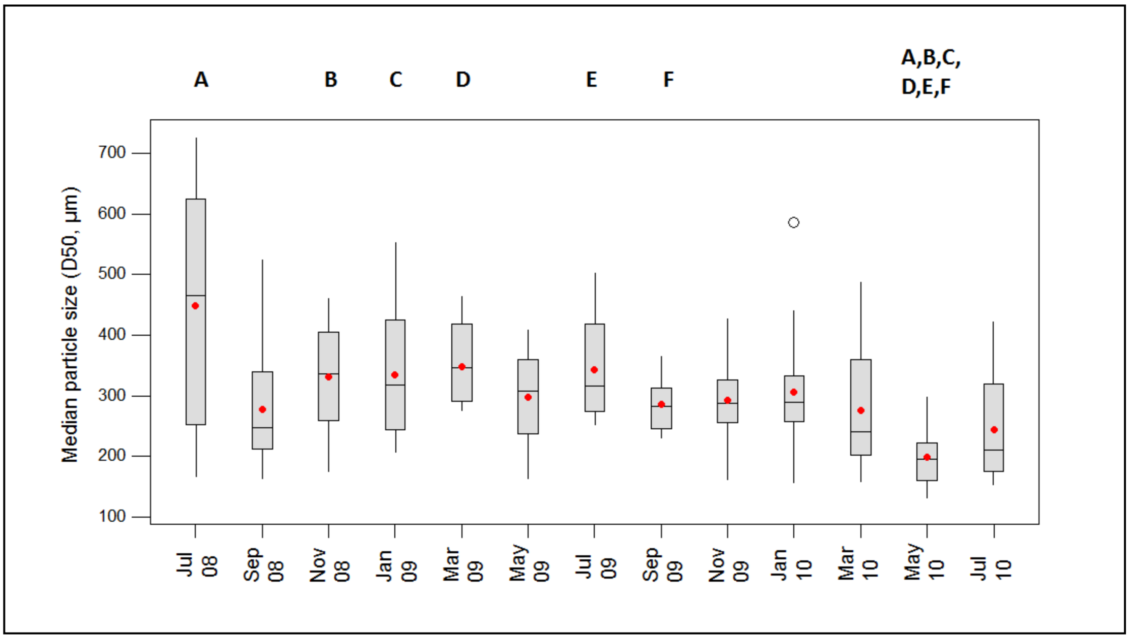


Figure 4.5 – A boxplot illustrating the changes of particle D_{50} values (µm) within effective sediment samples taken from *Ranunculus* patches on the Bere Stream at Snatford Bridge between July 2008 and July 2010. The box for each month represents the interquartile range with the horizontal bar in the box representing the median value, and red dot within the box representing the mean value. The whiskers extending from the box indicate the range of values within each month, with outlier values represented by open circles. The capital letters indicate the results from the series of *post-hoc* Mann-Whitney U-tests, where months with the same capital letters are those that possess D_{50} values that are significantly different from one another.

4.1.5.2 Seasonal changes in D_{50} values of the absolute particle sizes from the Bere Stream

Values of D_{50} within the absolute sediment fraction were determined for samples retrieved from the Bere Stream between July 2008 and July 2010 (Figure 4.6).

The absolute particle D_{50} dataset showed a seasonal pattern of variability. The mean particle D_{50} values of July 2008 and July 2009 were greater than the other months of the year. July 2008 had the highest mean particle D_{50} value within the two year dataset (523 ±166 (SD) µm) and the greatest range within its samples from fine to coarse sand, between 145 and 765 µm. Mean particle D_{50} values within the absolute sediment fraction between September 2008 and July 2010 remained within the fine-medium sand grade between 228 and 318 µm. The range of samples from September 2008 to July 2010 was between 88 and 587 µm from the very fine sand to coarse sand. November 2009 had the smallest mean D_{50} value (211 ± 42 (SD) µm), and the smallest range between its samples from 155 to 271 µm when outlier values were removed.

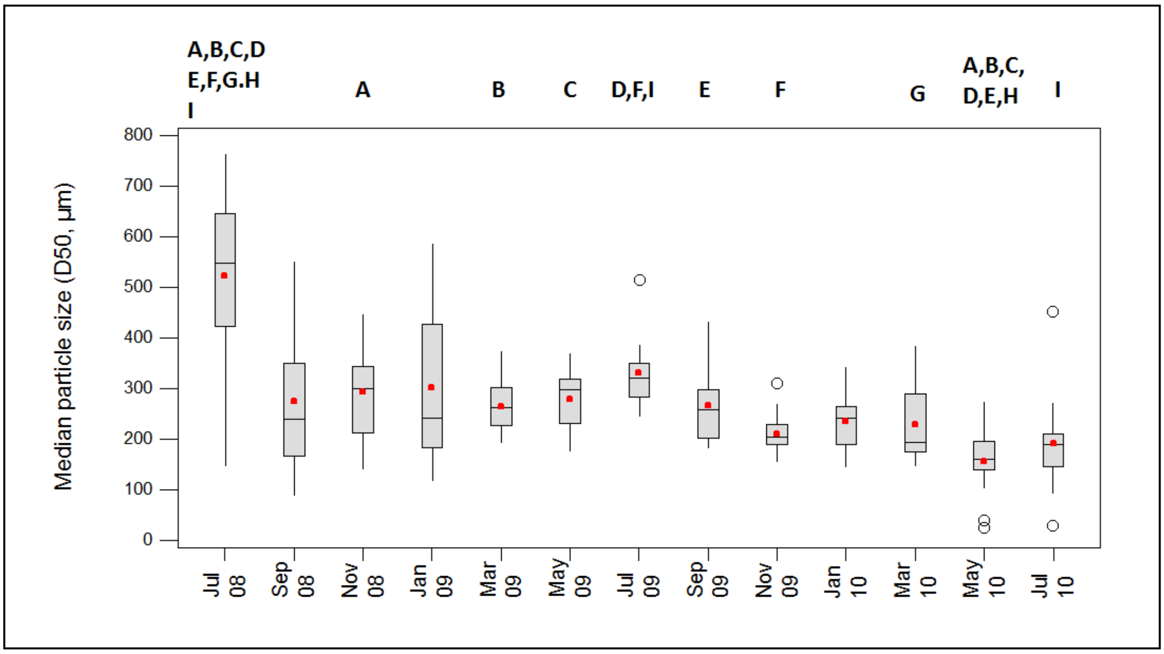


Figure 4.6 – A boxplot illustrating the changes of particle D_{50} values (µm) within absolute sediment samples taken from *Ranunculus* patches on the Bere Stream at Snatford Bridge between July 2008 and July 2010. The box for each month represents the interquartile range with the horizontal bar in the box representing the median value, and red dot within the box representing the mean value. The whiskers extending from the box indicate the range of values within each month, with outlier values represented by open circles. The capital letters indicate the results from the series of *post-hoc* Mann-Whitney U-tests, where months with the same capital letters are those that possess D_{50} values that are significantly different from one another.

Statistical analyses were used to determine if significant differences were present between months for values of particle D_{50} within the absolute sediment fraction. Datasets from each month were considered to be non-parametric because the observations were median values. A Friedman test determined that there was a highly significant difference (*d.f.* 12, ***P*** <0.001) between all of the months regarding absolute particle D_{50} values. A series of *post-hoc* Mann-Whitney U-tests with Bonferonni Correction (alpha value = 0.0006) were used to compare all months against each other for differences in absolute values of particle D_{50} (Figure 4.6). The tests determined that the particle D_{50} values from each sampling month except September 2008 were significantly different to those from July 2008. Particle D_{50} values in July 2009 were significantly different to those from November 2009 and July 2010. Values of absolute particle D_{50} values from May 2010 were significantly different to those from November 2008, March 2009, May 2009, July 2009 and September 2009 sample months.

4.1.5.3 Differences between effective and absolute median particle size on the Bere Stream

A Friedman test was used to analyse for differences between effective and absolute median particle sizes between all months within the two year dataset as it the closest non-parametric equivalent to a two-way ANOVA (Dytham, 2003). Effective and absolute median particle size fractions were found to be significantly different to one another (*d.f.* 1, ***P*** = 0.002), with mean values of particle D_{50} from absolute sediment samples being smaller in comparison with those from effective samples.

4.1.5.4 Seasonal changes in the % volume of silt and clay sized particles within the effective sediment fraction on the Bere Stream

Throughout the entire sampling period the % volume of silt and clay sized particles (%SC hereafter) within the effective sediment was <24 % (Figure 4.7). Notable increases in mean %SC values were observed in May 2009, May 2010 and July 2010 at 10.5 ± 3.8 (SD), 14.2 ± 4.8 (SD) and 12.7 ± 5.4 (SD) % respectively. Otherwise there was little difference between months in terms of mean %SC values. Large sample ranges for %SC were present for several months including July 2008, September 2008, May 2009 and all the months from November 2009 to July 2010.

May 2010 had the greatest mean %SC value within the effective sediment fraction. The month with the greatest sample range of %SC within the effective sediment fraction was July 2008 with 17.5 %. The month with the lowest mean %SC was July 2008 (5.0 ± 5.2 (SD) %), and the lowest sample range was observed in September 2009 with 6.4 %.

Statistical analyses were performed on the %SC values within the effective sediment fraction to determine if significant differences were present between sample months. Values were transformed into arcsine values prior to any analyses being performed. Datasets of each month were tested for normality using an Anderson-Darling test, all datasets were determined to be normally distributed (***P*** >0.05). A one factor repeated measures Analysis of Variance (ANOVA) determined that there was a highly significant difference (*d.f.* = 12, ***P*** <0.001) in the values of %SC between all

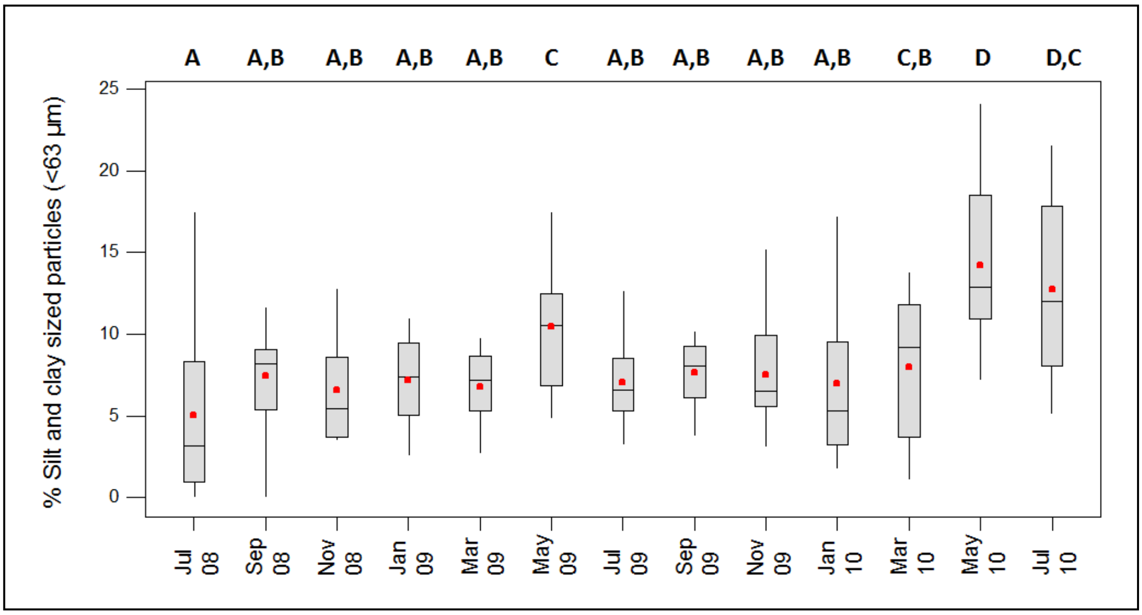


Figure 4.7 – A boxplot illustrating the changes in the % volume of silt and clay sized particles (%SC) within effective sediment samples taken from *Ranunculus* patches on the Bere Stream at Snatford Bridge between July 2008 and July 2010. The box for each month represents the interquartile range with the horizontal bar in the box representing the median value, and red dot within the box representing the mean value. The whiskers extending from the box indicate the range of values within each month, with outlier values represented by open circles. The capital letters indicate the results of the *post-hoc* Fishers LSD test, where months with the same capital letters are those that possess %SC values that are not significantly different from one another.

months. A *post-hoc* Fishers LSD test was used to compare all months against each other for differences in values of %SC (Figure 4.7) because result of the initial test was significant. Effective %SC values within May 2010 were significantly different to those of the other months within the two years except July 2010. Values of %SC from July 2010 were significantly different to those from all other months except May 2010 and May 2009.

4.1.5.5 Seasonal changes in the % volume of silt and clay sized particles within the absolute sediment fraction on the Bere Stream

The majority of the % volume of silt and clay sized particles (%SC) within the absolute sediment samples was <30 % within the two year survey period (Figure 4.8). Both July 2008 and July 2009 had smaller mean %SC values compared to other months, at 5.1 ± 7.8 (SD) and 8.4 % 2.8 (SD) % respectively.

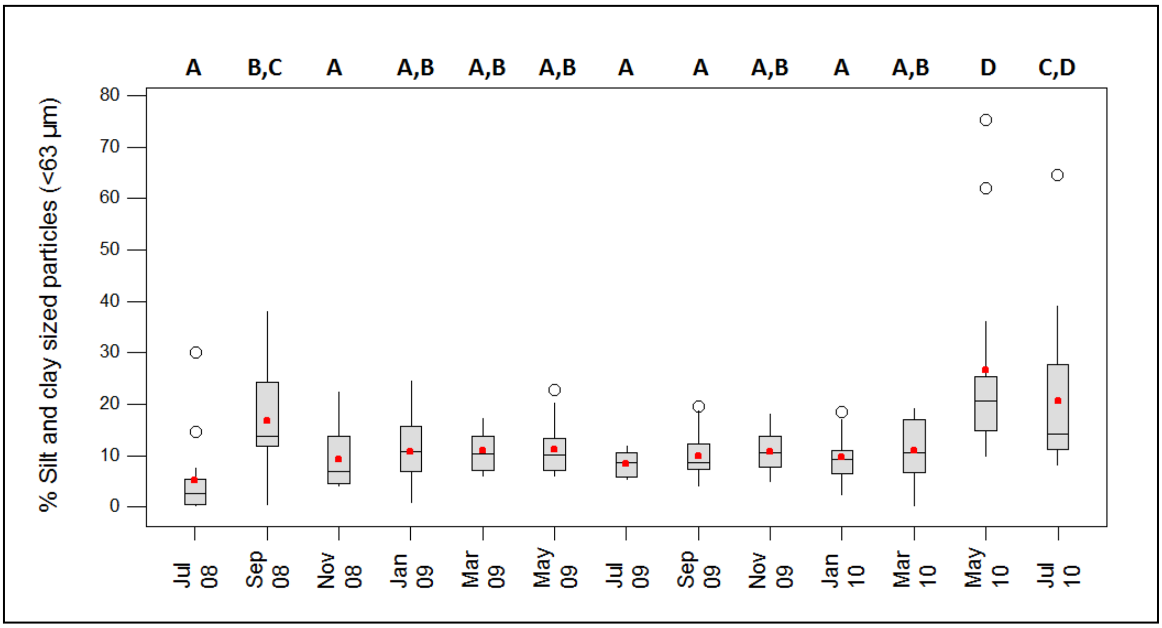


Figure 4.8 – A boxplot illustrating the changes in the % volume of silt and clay sized particles (%SC) within absolute sediment samples taken from *Ranunculus* patches on the Bere Stream at Snatford Bridge between July 2008 and July 2010. The box for each month represents the interquartile range with the horizontal bar in the box representing the median value, and red dot within the box representing the mean value. The whiskers extending from the box indicate the range of values within each month, with outlier values represented by open circles. The capital letters indicate the results of the *post-hoc* Fishers LSD test, where months with the same capital letters are those that possess %SC values that are not significantly different from one another.

There was considerable variability within the entire dataset, with many suspected outlier values present. Samples from September 2008, May 2010 and July 2010 were conspicuous compared to other months in the two year period as their absolute fractions had considerably greater mean %SC values at 16.7 ± 9.3 (SD) %, 26.7 ± 18.3(SD) and 20.7 ± 14.9 (SD) % correspondingly. September 2008 also had the greatest range of values between its samples of 38.0 % when suspected outlier values were excluded. July 2008 had the least mean %SC values. July 2009 had the least range between individual samples, with the range being 6.9 %.

Statistical analyses were performed on the arcsine transformed %SC values within the absolute sediment fraction to further investigate differences within the whole dataset. Datasets of each month were tested for normality using an Anderson-Darling test, and confirmed to be normally distributed (***P*** >0.05). A one factor repeated measures ANOVA determined that there was a highly significant difference between all months (*d.f.* = 12, ***P*** <0.001) for values of %SC within the absolute sediment fraction. A *post-hoc* Fishers LSD test was used to compare all of the months within the dataset for differences in the values of %SC within the absolute sediment fraction (Figure 4.8). Values of %SC within May 2010 were significantly different to those from all other sample months except July 2010. The %SC values from January 2009, March 2009, May 2009, November 2009 and March 2010 were only significantly different to %SC values from May 2010 and July 2010.

4.1.5.6 Differences in the values of % volume of silt and clay sized particles between effective and absolute sediment fractions on the Bere Stream

A two-factor repeated measures ANOVA was used to test for significant differences in values of %SC between effective and absolute sediment fractions, and between sample months. There was a highly significant difference between the effective and absolute sediment fractions for values of %SC (*d.f.* = 1, ***P*** <0.001) within the two year period. There was a highly significant difference between all of the months over the two year period (*d.f.* = 12, ***P*** <0.001). The interaction between 'effective vs. absolute % volume of clay and silt' and 'sample months' was also highly significant (*d.f.* = 12, ***P*** = 0.008). The interaction plot of the analysis (Figure 4.9) indicates that significant differences

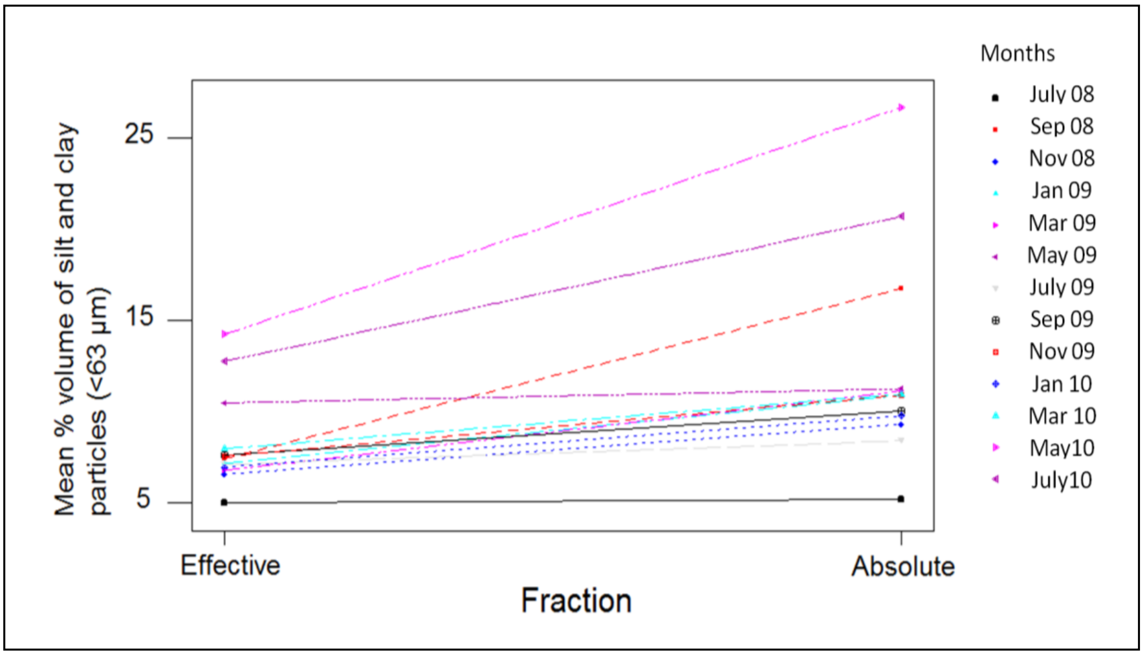


Figure 4.9 – The interaction between effective and absolute mean %SC values between sample months from sediment samples taken on the Bere Stream at Snatford Bridge between July 2008 and July 2010.

were present in %SC values between effective and absolute sediment fractions in September 2008, May 2010 and July 2010. Additionally, the plot suggests that the %SC values within September 2008, May 2010 and July 2010 were significantly different to those from the other sample months. The %SC values in July 2008 were significantly different to those of other months, but % SC values between the effective and absolute sediment fractions were not significant to one another in July 2008. All of the other months showed little significant differences in values of %SC between the effective and absolute sediment fractions, and there were no significant differences in values of %SC between those months.

4.1.5.7 Seasonal changes in the % organic matter content of fine sediment on the Bere Stream

The majority of sediment samples contained <10 % organic matter content (%OM hereafter) (Figure 4.10) throughout the survey period. The results revealed a high number of outlier values present within the %OM dataset. November 2009 had the highest outlying values within the dataset of 49.5 %.

High mean %OM values were present in July 2008, September 2008, September 2009, November 2009, May 2010 and July 2010. The month with the greatest mean value of %OM was September 2008 (6.7 ±7.5 (SD) %), the month with the least mean value was January 2010 (1.2 ± 0.6 (SD) %). The month with the largest %OM sample range (with outliers removed) was July 2008 (8.7 %), and the month with the smallest %OM sample range was July 2009 (1.8 %).

Statistical analyses were used to test for significant differences in the arcsine transformed values for %OM between sample months. All Bere Stream datasets were tested for normality using an Anderson-Darling test, the outcome of which was that all the datasets were determined as non-normally distributed ($\boldsymbol{P}$ <0.05). A Friedman test determined there was a highly significant difference (*d.f.* = 12, $\boldsymbol{P}$ <0.001) in %OM between all of the months that were analysed.

A series of *post-hoc* Mann-Whitney U-tests with Bonferonni Correction (alpha value = 0.0006) (Figure 4.10) determined the source of significant differences between sample months for values of %OM. The values of %OM in January 2010 were significantly different to those of July 2008, September 2008, May 2009 and May 2010.

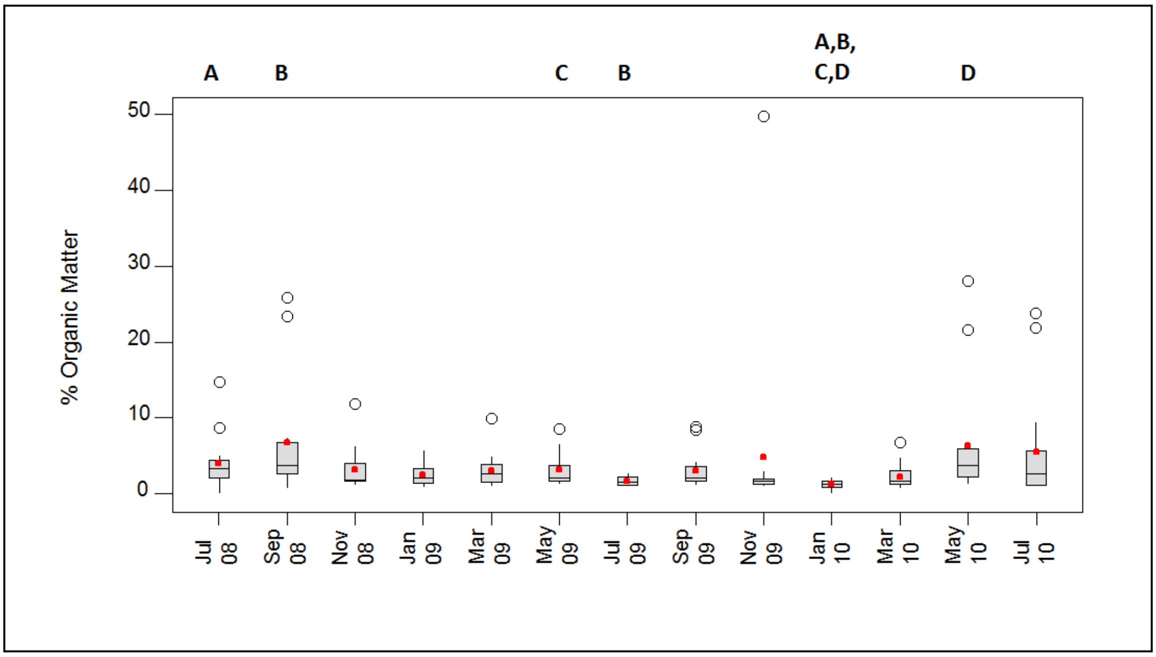


Figure 4.10– A boxplot illustrating the changes in % organic matter (%OM) within sediment samples taken from *Ranunculus* patches on the Bere Stream at Snatford Bridge between July 2008 and July 2010. The box for each month represents the interquartile range with the horizontal bar in the box representing the median value, and red dot within the box representing the mean value. The whiskers extending from the box indicate the range of values within each month, with outlier values represented by open circles. The capital letters indicate the results of the *post-hoc* Mann Whitney U-tests with Bonferonni Correction (alpha value = 0.0006) between months, where months with the same capital letters are those that possess %OM values that are significantly different from one another.

Additionally the %OM values from September 2008 were significantly different to those from July 2009.

4.1.5.8 Seasonal changes in the bulk density of fine sediment on the Bere Stream

Changes in the values of bulk density within fine sediment over the two year survey period were analysed (Figure 4.11). Bulk density was highly variable over the two year period. The range of the entire two year dataset not including suspected outlier values was between 253 and 1799 kg m^3. The greatest and least mean bulk density values during the survey period were in November 2009 (1528 ± 123 (SD) kg m^3) and September 2008 (902 ± 203 (SD) kg m^3) correspondingly. November 2008 had the highest sample range within the dataset from 380 to 1535 kg m^3, and the highest standard deviation (±316 kg m^3). The month with the least sample range without suspected outliers was in September 2009 from 1116 to 1402 kg m^3. November 2009 had the lowest standard deviation within the dataset.

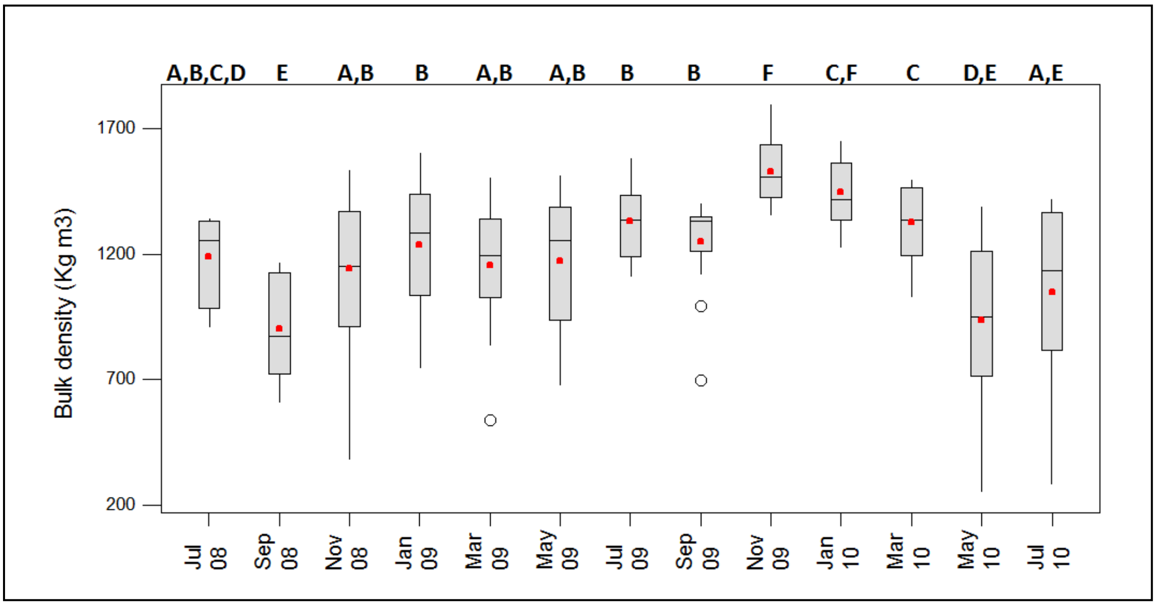


Figure 4.11– A boxplot illustrating the changes in bulk density values of sediment samples taken from *Ranunculus* patches on the Bere Stream at Snatford Bridge between July 2008 and July 2010. The box for each month represents the interquartile range with the horizontal bar in the box representing the median value, and red dot within the box representing the mean value. The whiskers extending from the box indicate the range of values within each month, with outlier values represented by open circles. The capital letters indicate the results of the *post-hoc* Fishers LSD test, where months with the same capital letters are those that possess bulk density values that are not significantly different from one another.

A set of statistical analyses were performed on the bulk density values to test for significant differences in between sample months. Bulk density datasets were tested for normality using an Anderson-Darling test, the outcome of which was that all the datasets were determined to be normally distributed (***P*** >0.05). A repeated measures ANOVA test confirmed that there were highly significant differences (*d.f.* = 12, ***P*** <0.001) in the bulk density values between months. A *post-hoc* Fishers LSD test was used to compare all months against each other for differences in bulk density (Figure 4.11) because result of the initial test was significant. The result of the *post-hoc* test revealed that there were many significant differences in bulk density between all of the months. Bulk density values within September 2008 were highly significantly different to all those of the other months within the dataset except May 2010 and July 2010. Bulk density samples from November 2009 were significantly different to samples from all months except January 2010. Bulk density values within sediment samples from July 2008 had the least significant differences with values from other sample months, and were only significantly different to September 2008 and November 2009.

4.1.5.9 Seasonal changes in D_{50} particle sizes within the effective sediment fraction from the River Frome

The D_{50} values of the effective fraction were determined within sediment samples retrieved from Frome Vauchurch between July 2008 and July 2010 (Figure 4.12).

Sediment samples from July 2008 had the greatest mean particle D_{50} value (378 ± 227 (SD) µm), and the greatest sample range from 155 to 878 µm. The sample ranges of September 2008, November 2008 and March 2009 were noticeably greater in comparison with other months in the dataset. The mean particle D_{50} values and sample range within March 2009 were particularly higher than the other months within the dataset. Values of particle D_{50} within the whole dataset were between very fine and coarse sand (79 to 878 µm). The mean particle D_{50} values of effective sediment samples within all sample months were between fine and medium sand, from 164 to 378 µm. March 2010 had the smallest mean particle D_{50} value (165 ± 22 (SD) µm) and the lowest sample range of all the sampled months, which was between 132 and 206 µm.

Statistical analyses were performed on the effective D_{50} dataset to further investigate differences between months over the two year period. A Friedman test was used to determine if there were significant differences between months because datasets containing median values are assumed to be non-parametric. The outcome of the test determined that there was a highly significant difference (*d.f.* = 12, ***P*** <0.001) in the effective particle D_{50} values between all sampled months within the dataset. Additional Mann-Whitney U-tests with Bonferonni Correction (alpha value = 0.0006) between months were performed (Figure 4.12) between all months within the dataset to determine which months were the most significantly different (***P*** <0.05) to one another (Dytham, 2003).

Effective D_{50} values from July 2008 and March 2009 were significantly different to samples from May 2010 and July 2010. There was also a significant difference between September 2008 and July 2010 for values of effective D_{50} within their sediment samples.

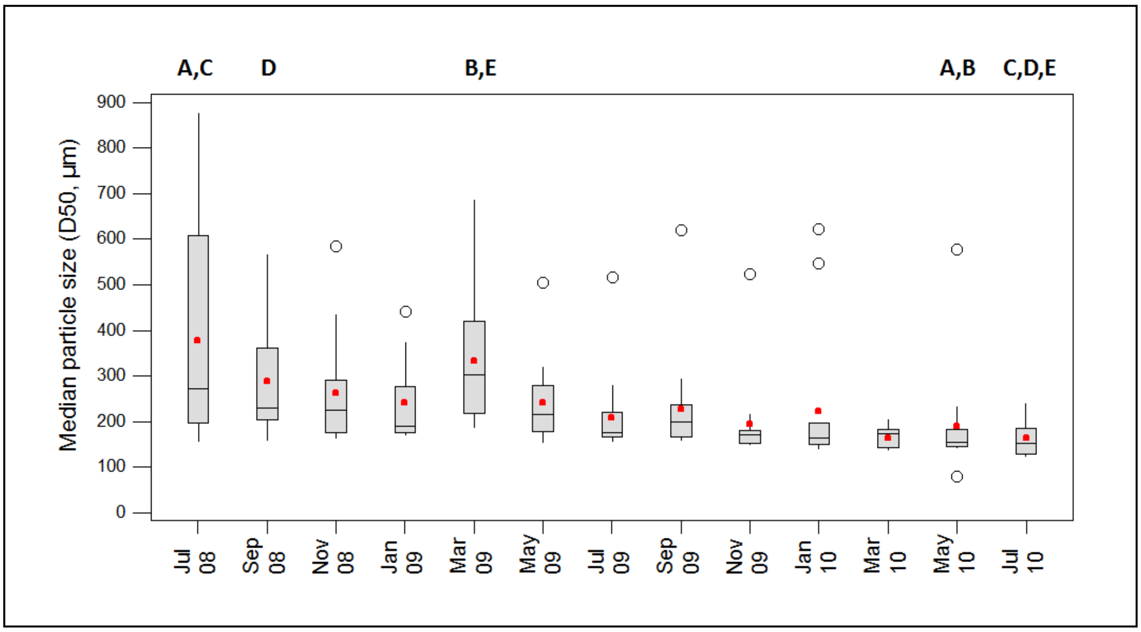


Figure 4.12 – A boxplot illustrating the changes of particle D_{50} values (µm) within effective sediment samples taken from *Ranunculus* patches on the River Frome at Frome Vauchurch between July 2008 and July 2010. The box for each month represents the interquartile range with the horizontal bar in the box representing the median value, and red dot within the box representing the mean value. The whiskers extending from the box indicate the range of values within each month, with outlier values represented by open circles. The capital letters indicate the results of the *post-hoc* Mann Whitney U-tests with Bonferonni Correction (alpha value = 0.0006) between months, where months with the same capital letters are those that possess D_{50} values that are significantly different from one another.

4.1.5.10 Seasonal changes in D_{50}values within the absolute sediment fraction from the River Frome

Values of D_{50} within the absolute fraction were determined from samples retrieved from Frome Vauchurch between July 2008 and July 2010 (Figure 4.13).

There appeared to be a decreasing trend over time, with mean particle D_{50} values generally decreasing throughout the two year period. The greatest mean particle D_{50} value was determined in July 2008 (390 ± 268 (SD) µm), which exceeded the mean particle D_{50} value of the effective fraction in July 2008. July 2008 had the greatest sample range which was between fine and coarse sand from 159 to 937 µm. The sample range for the whole dataset was between medium silt to coarse sand from 30 to 937 µm. May 2010 had the least mean particle D_{50} value (141 ± 33 (SD) µm) and the smallest sample range within the dataset within fine sand between 165 and 153 µm. There were a large number of sample outliers within the dataset, with outlier values present in

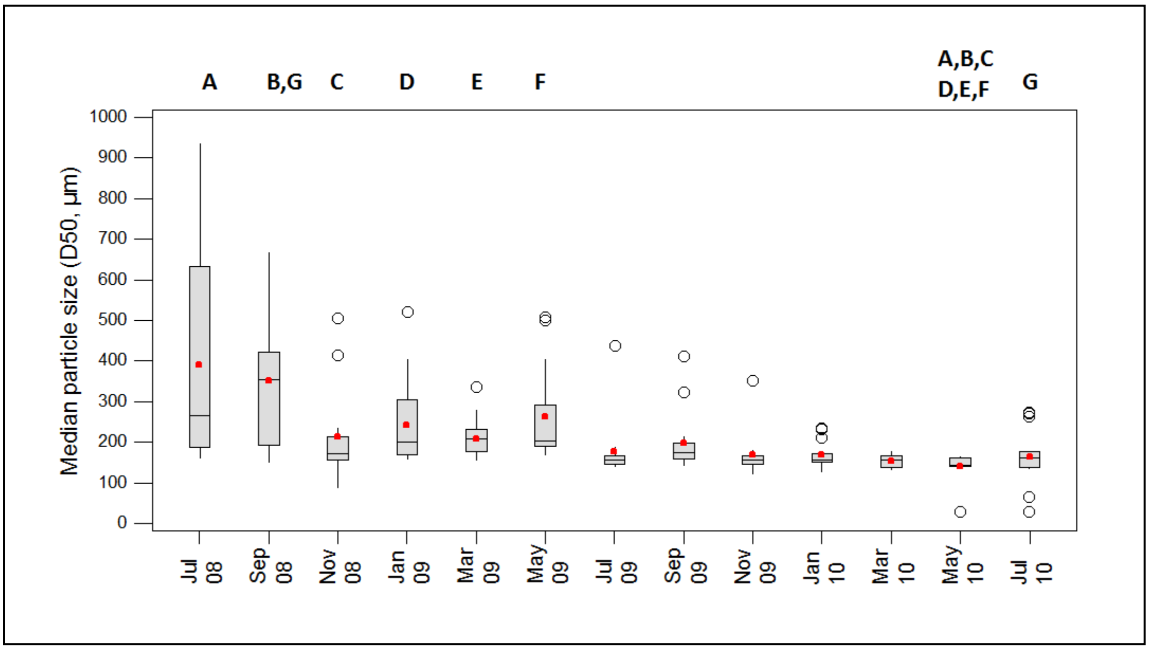


Figure 4.13 - A boxplot illustrating the changes of particle D_{50} values (µm) within absolute sediment samples taken from *Ranunculus* patches on the River Frome at Frome Vauchurch between July 2008 and July 2010. The box for each month represents the interquartile range with the horizontal bar in the box representing the median value, and red dot within the box representing the mean value. The whiskers extending from the box indicate the range of values within each month, with outlier values represented by open circles. The capital letters indicate the results of the *post-hoc* Mann-Whitney U-tests with Bonferonni Correction (alpha value = 0.0006), where months with the same capital letters are those that possess D_{50} values that are significantly different from one another.

November 2008, May 2009, September 2009, January 2010, May 2010 and July 2010.

Statistical analyses were used to determine significant differences between sample months for values of particle D_{50} within absolute sediment samples. Datasets of each month were determined to be non-parametric due to the median values. A Friedman test determined that there was a highly significant difference (*d.f.* = 12, ***P*** <0.001) in particle D_{50} values within the absolute sediment samples between months. Further *post-hoc* Mann-Whitney U-tests were performed with Bonferonni Correction (alpha value = 0.0006) (Figure 4.13) between all months within the dataset to determine which months were the most significantly different to one another.

Values of particle D_{50} within absolute sediment samples from the May 2010 sample month were significant different to those from all sampled months from July 2008 to May 2009. Additionally, absolute particle D_{50} values from July 2010 were significantly different to those from September 2008.

4.1.5.11 Differences between effective and absolute median particle size on the River Frome

A Friedman test was used to analyse differences between mean values for effective and absolute median particle sizes, and to assess the differences in effective and absolute mean median particle sizes between months. The Friedman test is the closest non-parametric equivalent of the two-way ANOVA (Dytham, 2003). Mean values were used because only one observation may be used for each factor combination. Factors in this case were mean particle D_{50} values from effective sediment against those from absolute sediment sample, as well as the significant differences between months within the dataset.

The results of the Friedman test indicated that there was no significant difference (*d.f.* = 1, ***P*** >0.05) between the mean values of particle D_{50} from the effective and absolute sediment.

4.1.5.12 Seasonal changes in the % volume of silt and clay sized particles within the effective sediment fraction on the River Frome

During the two year survey period the % volume of effective silt and clay sized particles (hereafter as %SC) within the sediment was between 1.7 and 41.8 % (Figure 4.14). The mean values of %SC appeared to steadily increase overall from July 2008 to July 2010. The months with the greatest and least sample range were January 2010 (10.2 %) and September 2008 (3.6 %) respectively. The greatest and least mean %SC values were observed in July 2010 (17.8 ± 4.4 (SD) %) and July 2008 (5.4 ± 3.6 (SD) %) correspondingly. Two suspected outlier values were found in sediment samples taken in July 2008, a further outlier value originated from a sediment sample taken in May 2010. The outlier value in May 2010 is particularly conspicuous, with 41.8 % of the sample volume being composed of silt and clay sized particles.

Statistical analyses were performed on the arcsine transformed values of %SC within effective sediment samples from Frome Vauchurch to further explore differences within the two year dataset. Values of %SC within each sample month were tested for normality using an Anderson-Darling test, and confirmed to be normally distributed (***P*** >0.05). A repeated measures one factor ANOVA determined that there was a highly significant difference (*d.f.* = 12, ***P*** <0.001) in the values of %SC between all months. A *post-hoc* Fishers LSD test was used to further compare all months against each other for differences in %SC values (Figure 4.14) because the result of the initial ANOVA test was significant.

The %SC values within effective sediment samples from March 2010 and May 2010 were significantly different to all other sample months, but not between each other. Values of %SC from July 2008 were significantly different to all months with the exception of September 2008, November 2008 and March 2009. September 2009 possessed sediment samples that were most similar to other sample months for values of %SC.

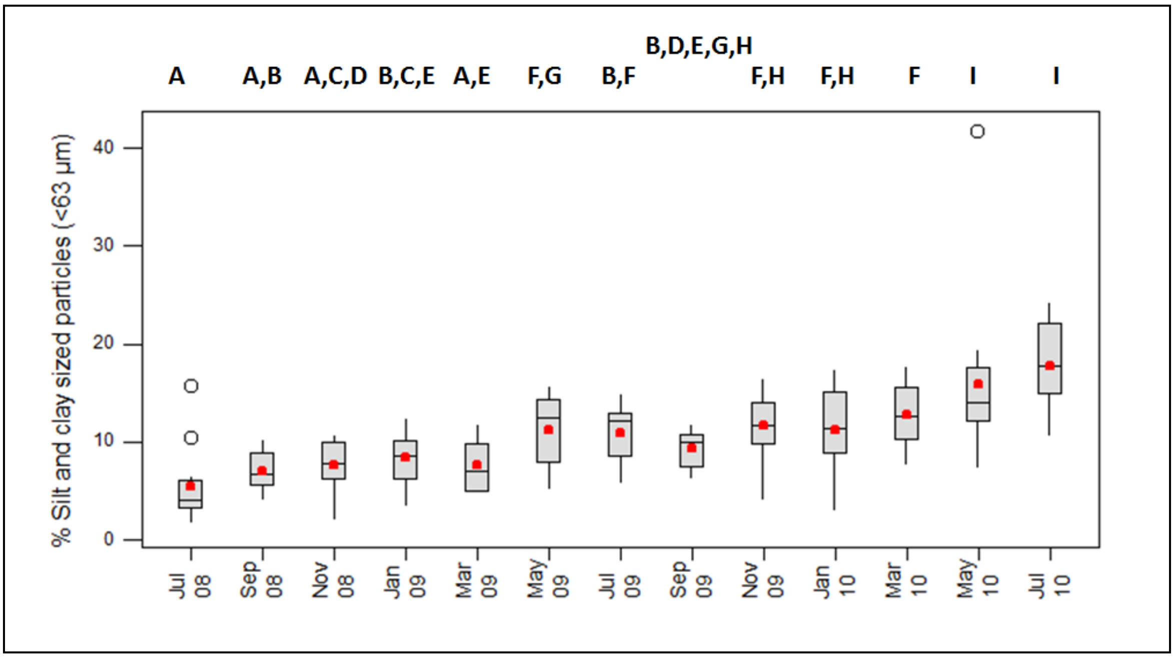


Figure 4.14 – A boxplot illustrating the changes in the % volume of silt and clay sized particles (%SC) within effective sediment samples taken from *Ranunculus* patches on the River Frome at Frome Vauchurch between July 2008 and July 2010. The box for each month represents the interquartile range with the horizontal bar in the box representing the median value, and red dot within the box representing the mean value. The whiskers extending from the box indicate the range of values within each month, with outlier values represented by open circles. The capital letters indicate the results of the *post-hoc* Fishers LSD test, where months with the same capital letters are those that possess %SC values that are not significantly different from one another.

4.1.5.13 Seasonal changes in the % volume of silt and clay sized particles within the absolute sediment fraction on the River Frome

The two year period of analysis revealed that the %SC values within absolute sediment from Frome Vauchurch appeared to increase over time (Figure 4.15), furthermore a noticeable increase did occur in July 2009 (13.1 ± 4.2 (SD) %) and July 2010 (18.7 ± 14.5 (SD) %). The range of %SC values from the entire survey period was between 0.4 and 69.1 %, when suspected outlier values were excluded. There were three samples which were considered suspected outliers within the survey period. The highest outlier value was 69.1 %, which was recorded in a sediment sample from May 2010.

Months with the greatest and lowest range of sample values for %SC within the absolute fraction were July 2010 (6.1 - 32.6 %) and November 2009 (6.7 – 10.8 %)

respectively when suspected outlying values were excluded. The greatest and least mean %SC values were from July 2010 and July 2008 with 18.7 % ±14.5 and 5.8 % ±9.0 correspondingly.

Statistical analyses were performed on the arcsine transformed values of %SC from absolute sediment samples to test for differences between sample months in the two year dataset. Values of %SC from each month were tested for normality using an Anderson-Darling test. The majority of the samples were determined to be normally distributed (***P*** >0.05), with a few being determined as non-parametric. The non-parametric result in those few months was most likely due to the presence of outlier values within the individual datasets. A one factor repeated measures ANOVA determined that there was a highly significant difference (*d.f.* = 12, ***P*** <0.001) in the %SC values within the absolute sediment fractions between months in the dataset. A *post-hoc* Fishers LSD test was used to further compare all months against each other for differences in absolute silt and clay % volume (Figure 4.15) because the result of the initial ANOVA test was significant.

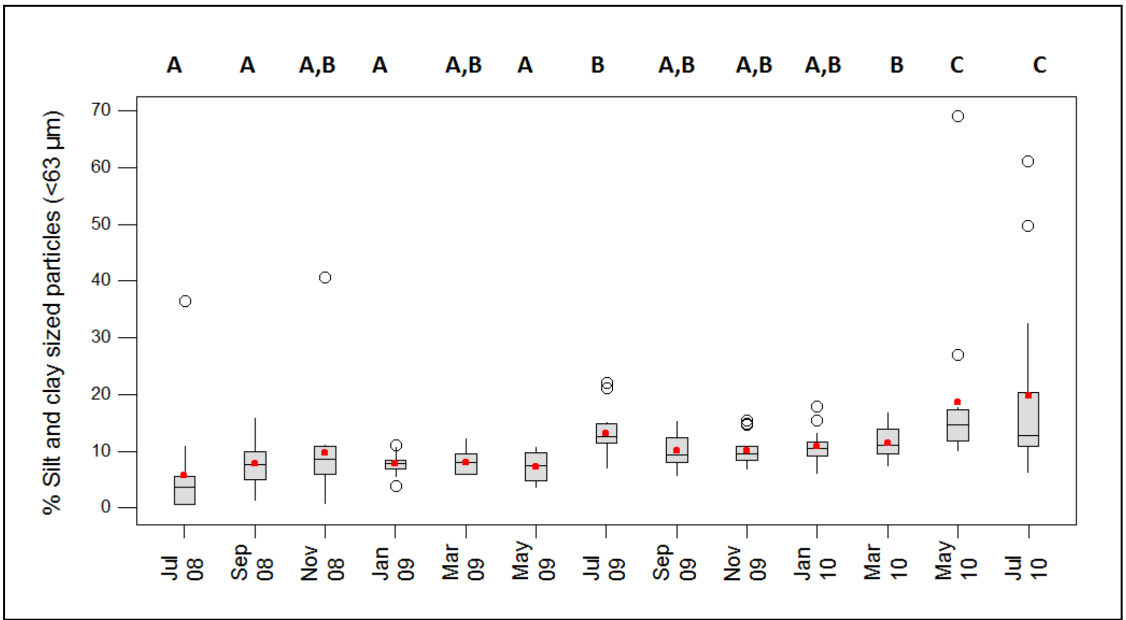


Figure 4.15 - A boxplot illustrating the changes in the % volume of silt and clay sized particles (%SC) within absolute sediment samples taken from *Ranunculus* patches on the River Frome at Frome Vauchurch between July 2008 and July 2010. The box for each month represents the interquartile range with the horizontal bar in the box representing the median value, and red dot within the box representing the mean value. The whiskers extending from the box indicate the range of values within each month, with outlier values represented by open circles. The capital letters indicate the results of the *post-hoc* Fishers LSD test, where months with the same capital letters are those that possess %SC values that are not significantly different from one another.

Values of %SC within absolute sediment samples from May 2010 and July 2010 were significantly different to all other months within the dataset, but not from each other. Values from the months of November 2008, March 2009, September 2009, November 2009 and January 2009 were only significantly different to values from May 2010 and July 2010.

4.1.5.14 Differences between effective and absolute % volume of silt and clay on the River Frome

A two-factor repeated measures ANOVA was used to test if there were significant differences between effective %SC and absolute %SC values, and significant differences between the months in which the sediment samples were taken. There was no significant difference (*d.f.* = 1, ***P*** >0.05) between the effective and absolute fractions in respect to % volumes of silt and clay sized particles over the two year study. Additionally, there was a highly significant difference between the months in which the samples were taken over the two year period (*d.f.* = 12, ***P*** <0.001). There was no significance in the interaction test for the analysis (*d.f.* = 12, ***P*** >0.05).

The interaction plot of the analysis (Figure 4.16) illustrates that all but a few of the interaction lines are horizontally parallel and close together. This indicates that in general there was no significant interaction between values of %SC within effective and absolute sediment fractions, and differences in %SC values within the effective and absolute samples were present between sample months. The plots for January 2009, May 2009, November 2009, May 2010 and July 2010 suggest that they possess significantly different values of %SC between the effective and absolute sediment samples. The interaction plot also suggests that %SC values within the effective and absolute fractions of July 2008, May 2010 and July 2010 were possibly significantly different to values within the other months.

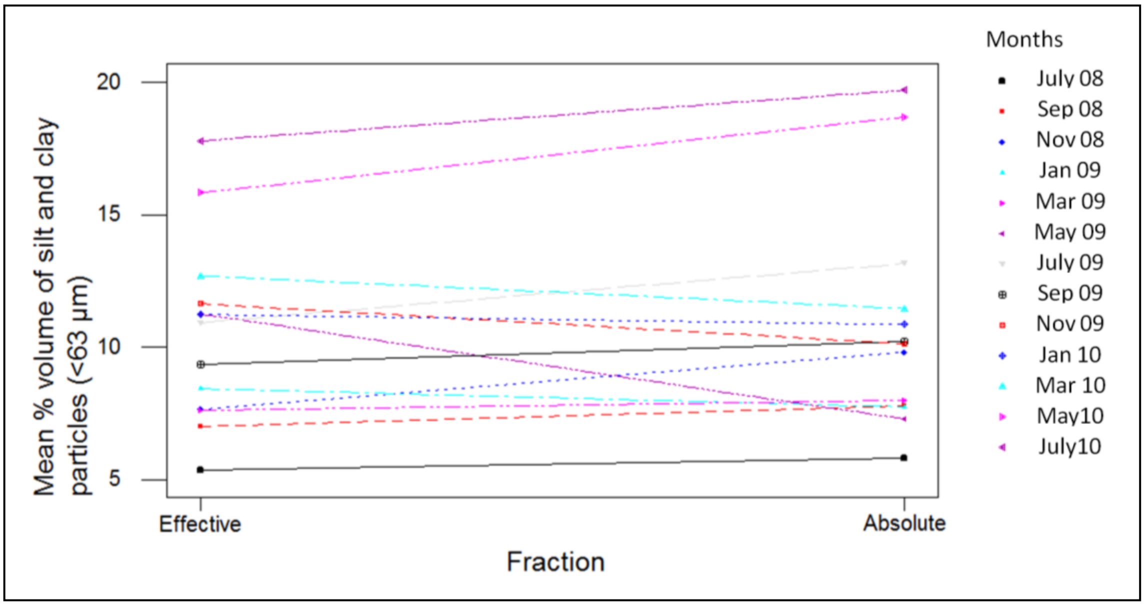


Figure 4.16 - The interaction of mean % volume of silt and clay sized particles between the effective and absolute sediment fractions within sediment samples taken from *Ranunculus* patches between July 2008 and July 2009 at FromeVauchurch.

4.1.5.15 Seasonal changes in the % organic matter content of fine sediment on the River Frome

The majority of the sediment samples retrieved from Frome Vauchurch contained less than 6 % organic matter (Figure 4.17). There were a large number of suspected outliers within the complete dataset, with some samples containing conspicuously greater % organic matter (henceforth as %OM) than other samples. This implies that there was a high variability of %OM values within the fine sediment samples throughout the two year survey period. The greatest outlier value was from sediment samples taken in July 2010 (28.1 %), which was also the greatest measurement of organic matter within the entire dataset.

There was a distinct seasonal pattern of %OM values within sediment samples from Frome Vauchurch, the pattern was more pronounced than samples from the Bere Stream taken during the same timescale. Mean %OM values gradually decreased from 3.8 ± 4.2 (SD) % in July 2008 to 1.6 ± 0.4 (SD) % in January 2009, it then increased to 4.6 ± 4.2 (SD) % in September 2009 before subsequently decreasing again to 2.2 ± 2.5 (SD) % in January 2010. The greatest mean %OM was from July 2010 and the least mean %OM value was from January 2009, at 5.6 ± 7.5 (SD) and 1.6 ± 0.4 (SD) % respectively. The months with the largest and smallest range in %OM (discluding suspected outlier values) were July 2010 and January 2009, with 12.3 and 1.5 % correspondingly.

Statistical analyses were performed on the arcsine transformed %OM dataset for significant differences between sample months. All Frome Vauchurch datasets were tested for normality using an Anderson-Darling test, the outcome of which was that all datasets were determined to be non-normally distributed ($\boldsymbol{P}$ <0.05). A Friedman test determined there was a highly significant difference (*d.f.* = 12, $\boldsymbol{P}$ <0.001) in %OM between all of the months that were analysed. A series of post-hoc Mann-Whitney U-tests with Bonferonni Correction (alpha value = 0.0006) were used to determine the source of significant differences between sample months for values of %OM (Figure 4.17).

A single significant difference was found between July 2008 and January 2009 for values of %OM.

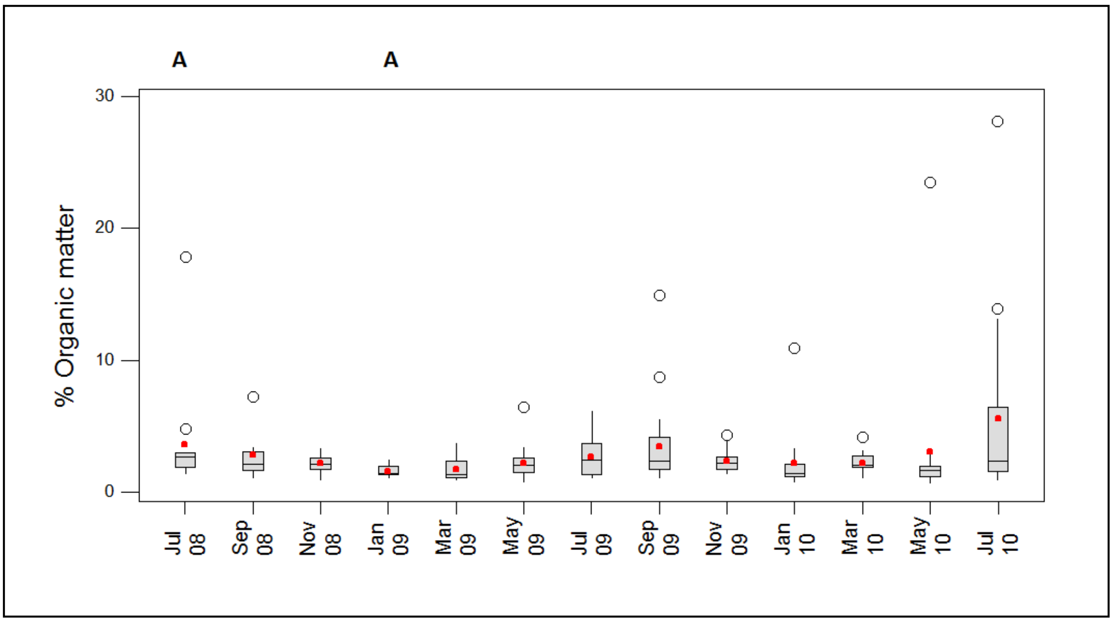


Figure 4.17 - A boxplot illustrating the changes in % organic matter (%OM) within sediment samples taken from *Ranunculus* patches on the River Frome at Frome Vauchurch between July 2008 and July 2010. The box for each month represents the interquartile range with the horizontal bar in the box representing the median value, and red dot within the box representing the mean value. The whiskers extending from the box indicate the range of values within each month, with outlier values represented by open circles. The capital letters indicate the results of the *post-hoc* Mann Whitney U-tests with Bonferonni Correction (alpha value = 0.0006) between months, where months with the same capital letters are those that possess %OM values that are significantly different from one another.

4.1.5.16 Seasonal changes in the bulk density of fine sediment on the River Frome

The change in bulk density at Frome Vauchurch over the two year period was also analysed (Figure 4.18). There were large seasonal variations in mean bulk density over the two year period. Large variations in bulk density were apparent in July 2009 (1003 ± 247 (SD) kg m^3) and July 2010 (973 ± 426 (SD) kg m^3), where mean bulk density was much less in comparison with other months. The range of the whole two year dataset not including suspected outlier values was between 123 and 1782 kg m^3.

The greatest mean value within the dataset was in November 2009 (1400 ± 242 (SD) kg m^3). The month of July 2010 had the greatest range in individual samples (1394 kg m^3) and the greatest standard deviation from the mean value. March 2010 had the least range within individual samples (333 kg m^3) and the lowest standard deviation from the mean value (±104 kg m^3). Two suspected outlier values were present within the month of November 2009, and a third value was within sediment samples from May 2010.

Statistical analyses were used to test for significant differences in bulk density values between months. All bulk density datasets were tested for normality using an Anderson-Darling test, the outcome of which was that all the datasets were determined as normally distributed ($\boldsymbol{P} > 0.05$). A one factor repeated measures ANOVA test confirmed that there were highly significant differences (*d.f.* = 12, $\boldsymbol{P} < 0.001$) in the bulk density values between months. A *post-hoc* Fishers LSD test was used to further compare all months against each other for differences in bulk density (Figure 4.18). The test confirmed that the bulk density samples from July 2010 were significantly different to those of all other months within the two year dataset, with the exception of those from July 2009. Bulk density values from July 2009 were significantly different to other months with the exception of September 2009, March 2010 and July 2010. Bulk density values from sediment sampled in March 2010 were only significantly different to those from July 2010.

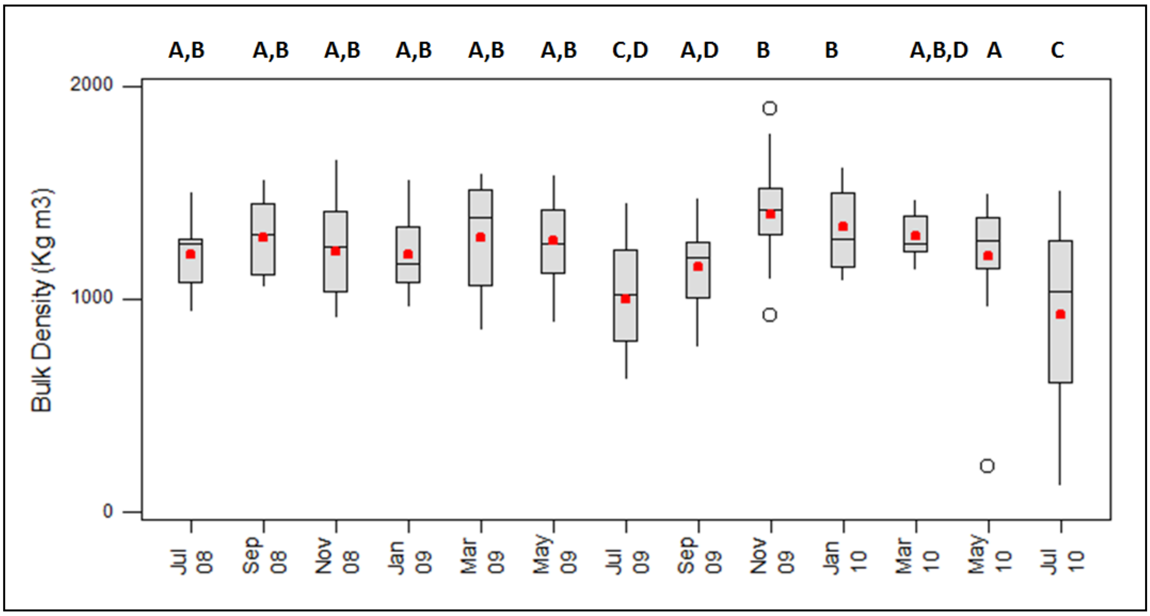


Figure 4.18 – A boxplot illustrating the changes in bulk density values of sediment samples taken from *Ranunculus* patches on River Frome at Frome Vauchurch between July 2008 and July 2010. The box for each month represents the interquartile range with the horizontal bar in the box representing the median value, and red dot within the box representing the mean value. The whiskers extending from the box indicate the range of values within each month, with outlier values represented by open circles. The capital letters indicate the results of the *post-hoc* Fishers LSD test, where months with the same capital letters are those that possess bulk density values that are not significantly different from one another.

4.1.6 Reach scale surficial fine sediment cover

This section reports on the reach scale fine sediment cover which was analysed using a GIS. The GIS produced maps of estimated sediment cover and distribution that could be compared with vegetation cover maps (See Section 4.1). Using the GIS it was also possible to produce estimates of sediment volume (m^3) for the entire reach, and sediment volume estimates underlying specific macrophyte patches.

4.1.6.1 Bere Stream, July 2008 – July 2010

The changing distribution of surficial fine sediment from July 2008 to July 2010 on the Bere Stream reach is illustrated in Figure 4.19. By comparing the vegetation cover and fine sediment distribution it can be deduced that distribution of fine sediment from month to month was mostly confined to macrophyte patches. From analysing the GIS maps it was apparent that *Ranunculus* and *Nasturtium* possessed similar volumes of sediment within their patches, suggesting that they are equally efficient in retaining fine sediment within their beds.

Fine sediment was commonly found within the margins in the majority of the months surveyed. The left bank of the reach was particularly retentive due to a sizable abundance of marginal macrophyte species alternating between majority *Nasturtium* (e.g. from September 2009 to November 2009) or *Apium*. Fine sediment was present within the centre of the channel when there were sufficient *Ranunculus* patches within the same location to provide a shelter from the higher flow velocities. In a number of cases *Nasturtium* colonised and grew over *Ranunculus* patches *c.f.* the period from July 2008 to January 2009, and also July 2010. The majority of fine sediment retained within the channel was stabilised by *Ranunculus* patches prior to the incursion of *Nasturtium*. In periods of seasonally low macrophyte cover (e.g. January 2010) the number of fine sediment patches decreased within the reach, and individual patches were smaller. Fine sediment patches would become deepened and larger with increasing seasonal macrophyte growth, reflecting an increasing capacity for localised fine sediment retention.

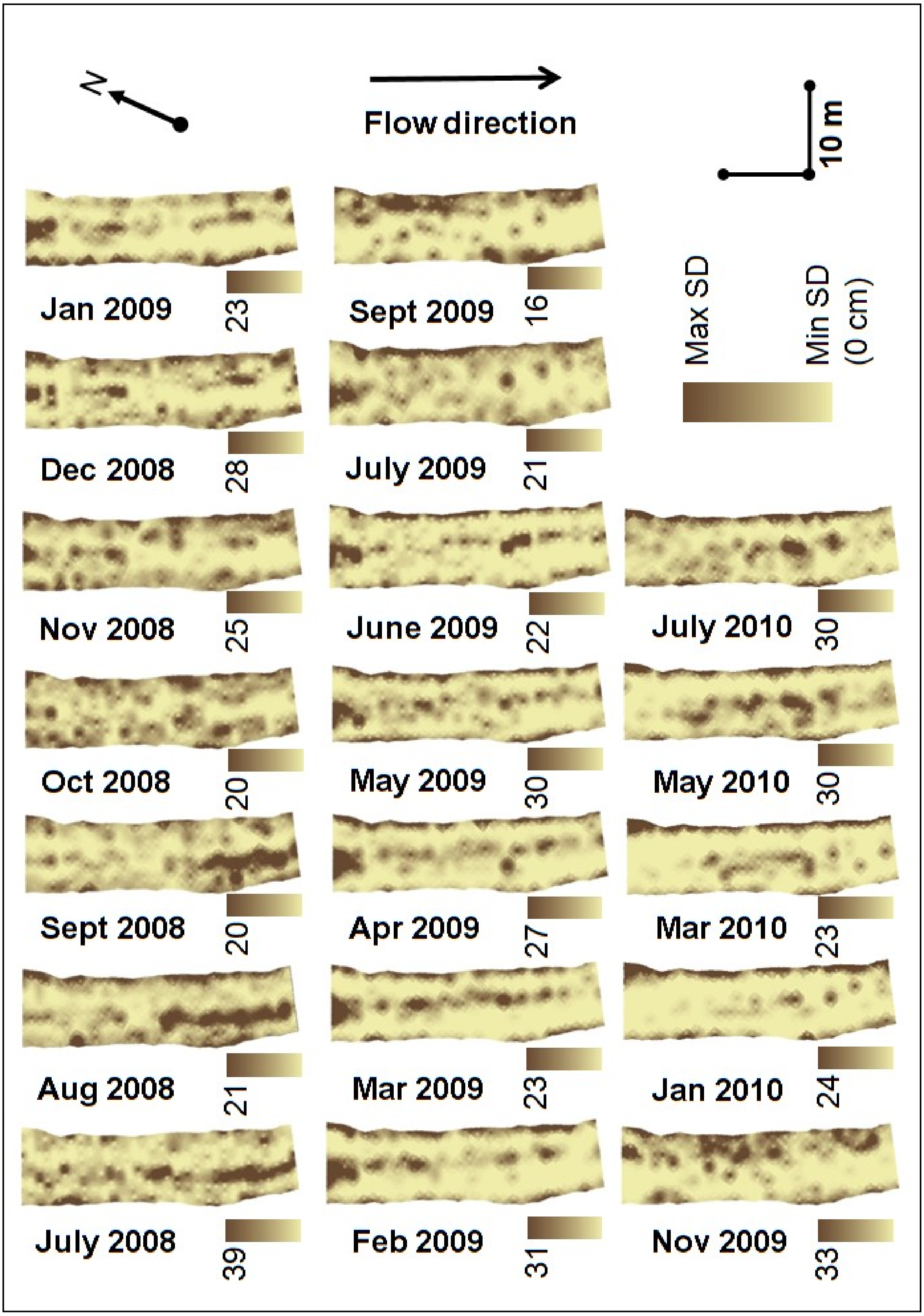


Figure 4.19 – The change in distribution and depth (SD, cm) of surficial fine sediment within the Bere Stream between July 2008 and July 2010, the darkest brown patches indicate deepest deposits. The maximum sediment depth for each sample month is notated.

Monthly changes in fine sediment weight for the entire reach are illustrated in Figure 4.20. Measurements of bulk density (kg m^3) from sediment analyses (See Section 3.2.7) were used to convert sediment volume (m^3) into weight of fine sediment (kg). In months where no sediment samples were collected, an estimate of the bulk density was produced by calculating a mean value from sediment sample values of the months adjacent to the months without values.

There was a decrease in the total weight of fine sediment within the reach between July 2008 and September 2008 from 6425 to 3500 kg respectively. This decrease was possibly due to the decline in *Ranunculus* cover in the centre of the channel leading a loss of fine sediment. An increase in sediment weight then followed from September 2008 to just 4825 kg in December 2008, this may have been attributed to the remerging growth of *Ranunculus* cover. The decreased *Nasturtium* growth in the margins between December 2008 and January 2009 resulted in a net loss of 675 kg of fine sediment from the margins. Between January and February 2009 an increase in fine sediment weight occurred due to increased sediment retention underneath the increasing *Ranunculus* growth at the top of the reach and within the centre of the channel. A further loss of 820 kg fine sediment took place between February and March 2009. This

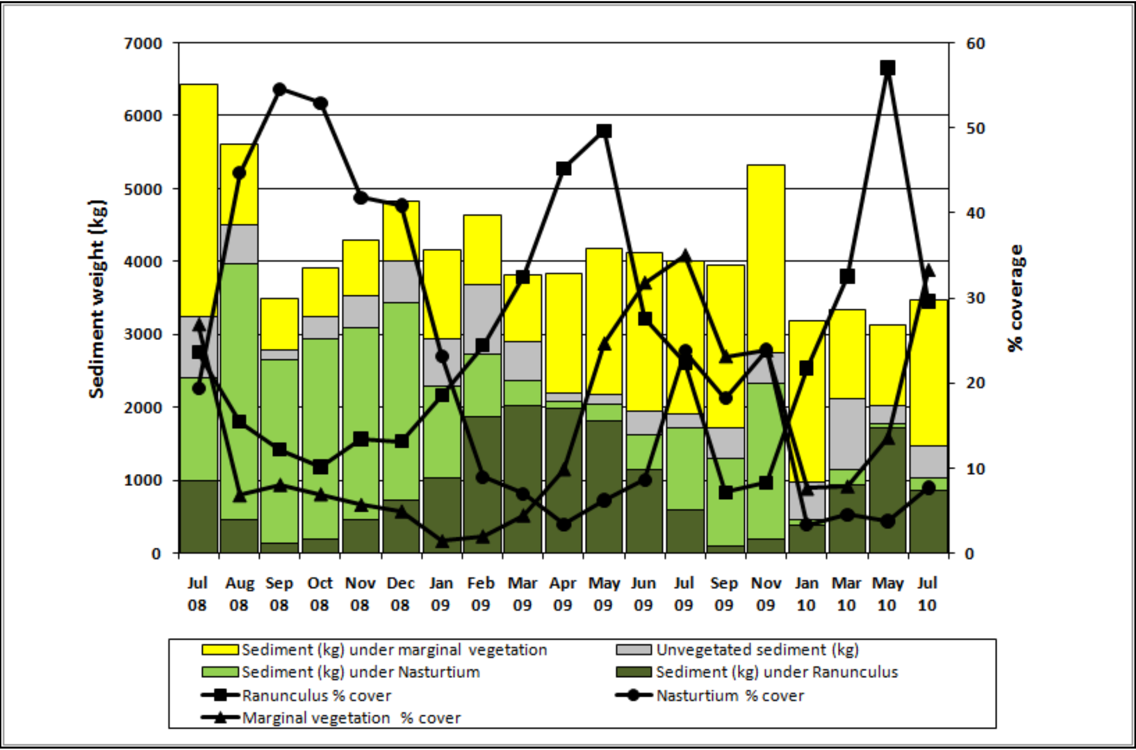


Figure 4.20- Temporal changes in the weight of sediment within patches of *Nasturtium*, *Ranunculus*, marginal vegetation and on top of unvegetated gravel on the Bere Stream at Snatford Bridge between July 2008 and July 2010.

was most likely due to further loss of *Nasturtium* cover from the margins to just 2 %, and a loss of fine sediment from underneath the *Ranunculus* at the top of the reach. From March to September 2009 there were only slight changes in the amount of fine sediment within the whole reach. There was a subsequent in fine sediment within the reach during November 2009 at 5318 kg which coincided with an increase in *Nasturtium* area cover to 24 %. Following the seasonal decline of *Nasturtium* cover in January 2010 a corresponding decrease in the total weight of sediment also occurred. There was very little variation in the total weight of fine sediment within the reach between January and July 2010, even though vegetation cover during the period varied considerably.

In all survey months the combined weight of fine sediment underneath *Ranunculus* and *Nasturtium* did not equal the total weight of fine sediment within the reach. This was due to the substantial distributions of fine sediment underneath the marginal vegetation dominated by *Apium*, in addition to the smaller patches of surficial fine sediment deposits on top of unvegetated gravel within the channel (Figure 4.20).

There was a seasonal pattern in the volume of fine sediment per m^2 of *Ranunculus* and *Nasturtium* over time (Figure 4.21). The volume (m^3) of fine sediment

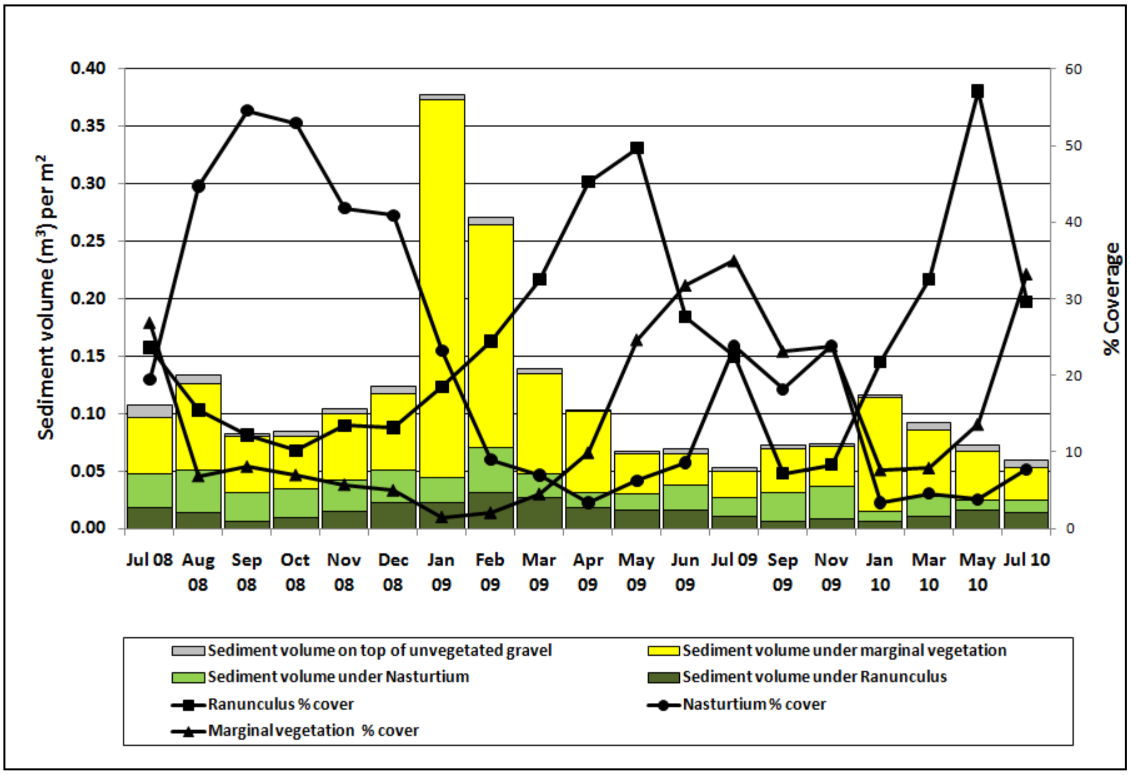


Figure 4.21 – The changes of fine sediment volume (m^3) per m^2 of *Ranunculus*, *Nasturtium*, marginal vegetation and unvegetated gravel on the Bere Stream at Snatford Bridge between July 2008 and July 2010.

per m^2 of *Ranunculus* was least and greatest during September 2008 and February 2009 correspondingly at 0.006 and 0.031 m^3 per m^2 respectively. The months with the lowest volume of sediment per m^2 within *Nasturtium* cover were January 2010 and May 2010 at 0.009 m^3 per m^2, and the month with the greatest volume per m^2 was in February 2009 at 0.039 m^3 per m^2. Overall, *Nasturtium* had the greater volumes of fine sediment per m^2, although there were exceptions in March 2009, April 2009, May 2010 and July 2010 where there was a greater volume of fine sediment per m^2 of *Ranunculus* at 0.026, 0.018, 0.016 and 0.014 m^3 per m^2 correspondingly. The marginal vegetation that was primarily composed of *Apium* possessed considerably higher estimates of sediment volume per m^2 compared with that of *Ranunculus* and *Nasturtium* combined. The greatest volume of sediment observed within patches of marginal vegetation was during January 2009 at 0.33 m^3 per m^2.

4.1.6.2 Frome Vauchurch, July 2008 –July 2010

Changing fine sediment distribution between July 2008 and July 2010 is illustrated in Figure 4.22. There was a pattern of surficial fine sediment storage within the reach that corresponded with seasonal changes in macrophyte cover and channel discharge. As the surveys progressed the channel bed appeared to lose fine sediment in open areas of the channel as *Ranunculus* patches became more fragmented. Subsequently, large deposits of fine sediment were only distributed underneath the most stable and resilient *Ranunculus* patches.

Throughout the survey period the left margin of the channel was a refuge for significant deposits of fine sediment. The most upstream left bank had long-term deposits of unvegetated fine sediment. This was due to the presence of a bush of bramble and tree debris that had encroached into the stream channel immediately upstream of the deposit location, and this was present throughout the two year survey period. The low flow velocities present in this area of the reach appeared to promote sediment deposition, possibly due to low sediment erosion and high sediment stability.

There was a large deposition of fine sediment underneath the *Ranunculus* patches that were adjacent to the right bank and between transects 16 to 24. This sediment patch persisted from July 2008 until after the September 2009 sample month. The sediment patch was subsequently lost between the September 2009 and November 2009 surveys. Throughout the July 2008 to September 2009 period the sediment patch

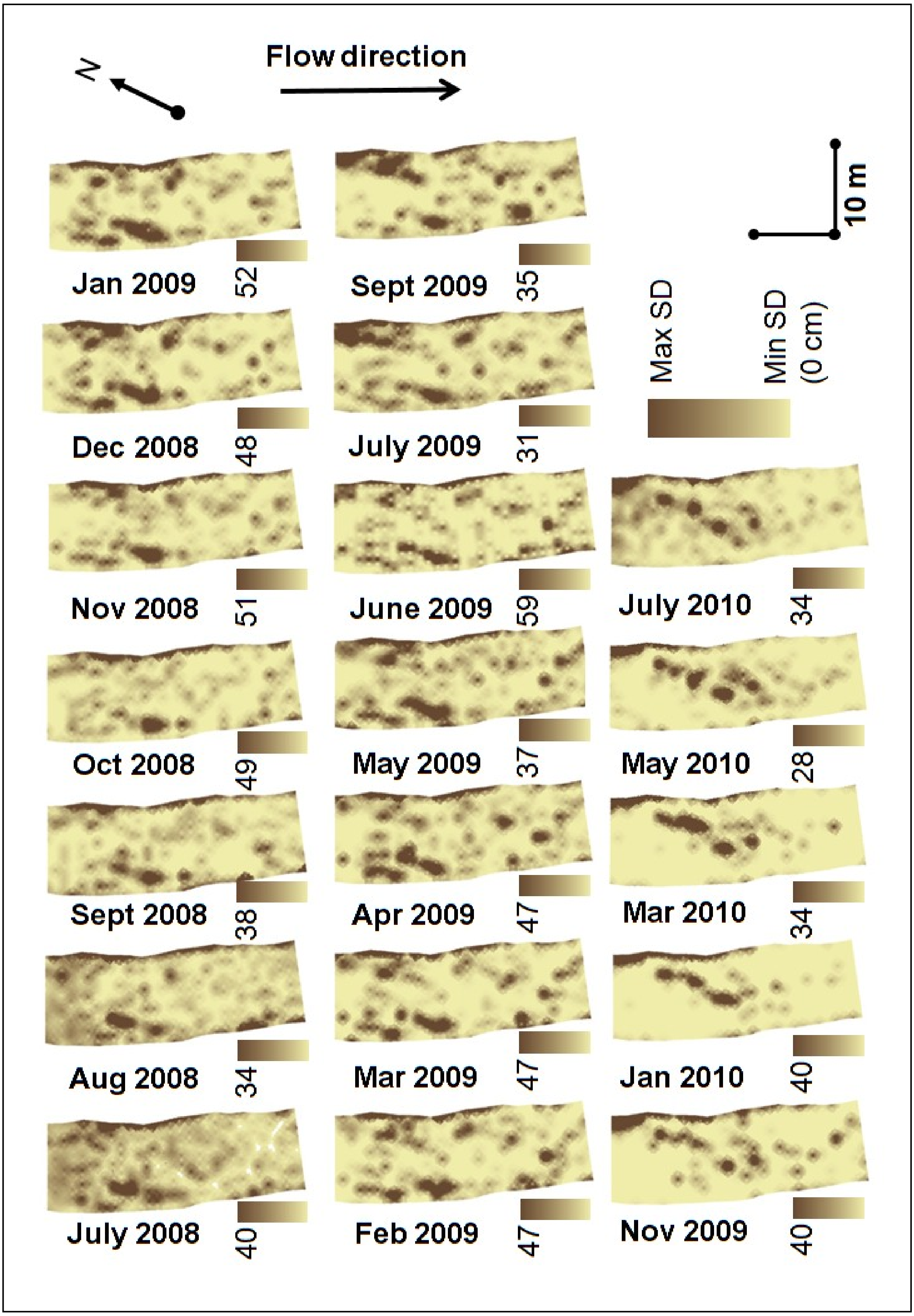


Figure 4.22 - The change in distribution and depth (SD, cm) of superficial fine sediment within the reach on the River Frome at Frome Vauchurch between July 2008 and July 2010, the darkest brown patches indicate deepest deposits. The maximum sediment depth for each map is notated.

changed shape, position, and size considerably. The greatest spatial extent of the patch was between the December 2008 and January 2009. Between November 2009 and July 2010 a chain of interconnecting fine sediment patches were formed within the centre of the channel underneath *Ranunculus* patches.

Measurements of bulk density (kg m^3) from sediment analyses were used to convert sediment volume (m^3) into weight estimates of fine sediment (kg). In months where no sediment samples were collected, an estimate of bulk density was produced by calculating a mean value from measured values from sample months prior and immediately following.

Figure 4.23 describes the change in the total weight of fine sediment deposited within the channel and the weight of fine sediment underneath *Ranunculus* patches in kg. The amount of fine sediment deposited directly within *Ranunculus* patches was approximately half the total weight of fine sediment deposited within the channel. Considerable deposits of fine sediment were present within the unvegetated section within the upstream left bank area, as well as underneath encroaching marginal vegetation on the left bank. It is also worth noting that sandy deposits were seen to extend downstream of the trailing fronds of some *Ranunculus* patches during the survey period. In these cases deposits were classified as unvegetated by the GIS, even though the reason for their presence was the result of a *Ranunculus* patch immediately upstream.

The total weight of fine sediment decreased considerably from 6550 kg in July 2008 to 3538 kg in October 2008, the weight of sediment then increased notably to 5990 kg in November 2008. From November 2008 to June 2009 total sediment weight did not vary considerably. The difference in weight between November 2008 and June 2009 was just ±0.27 kg. The largest weight of sediment in the dataset occurred in January 2009 at 6660 kg. In July 2009 there was a substantial decrease in total weight to 4935 kg, which was attributed to a decrease in the average bulk density of samples in July 2009 (1003 kg m^3). This was followed by an increase to 6041 kg in September 2009 and a subsequent gradual decrease to 3187 kg in March 2010. Between March and July 2010 the total weight of sediment did not increase greatly, with the difference being 333 kg

The volume of deposited fine sediment (m^3) per m^2 of *Ranunculus* during the survey period is illustrated in Figure 4.24. The greatest values of fine sediment volume per m^2 of *Ranunculus* were found in both January 2009 and January 2010.

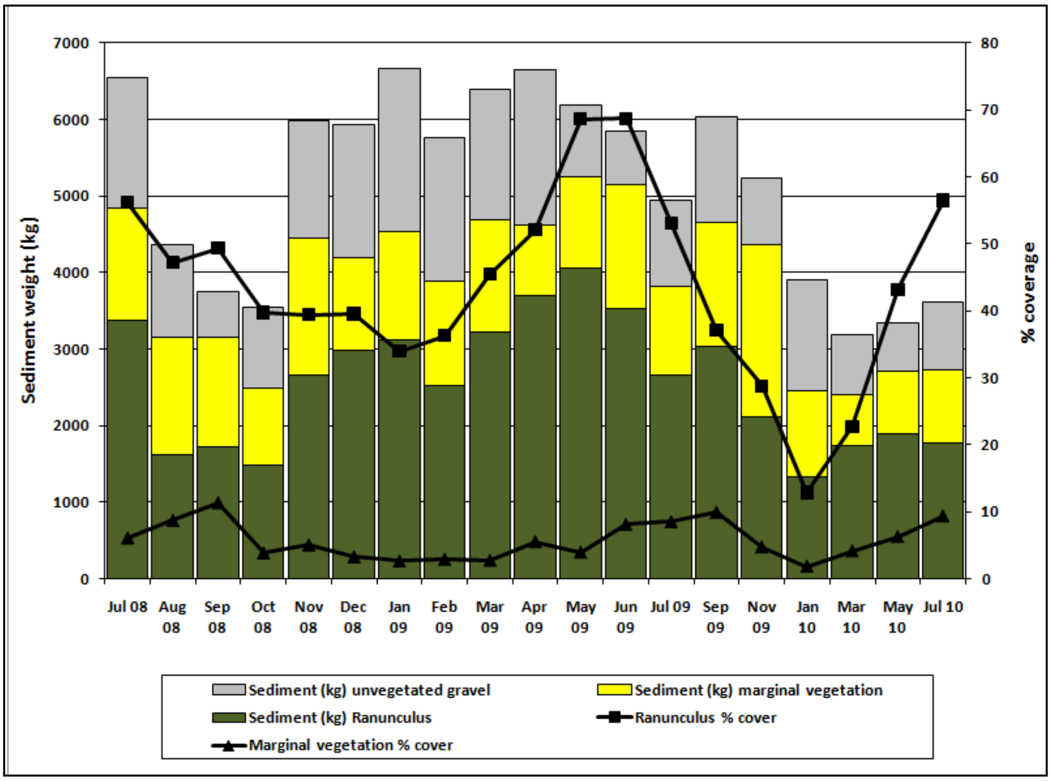


Figure 4.23 – Temporal changes in the weight of sediment (kg) within patches of *Ranunculus*, marginal vegetation and on top of unvegetated gravel on the River Frome at Frome Vauchurch between July 2008 and July 2010.

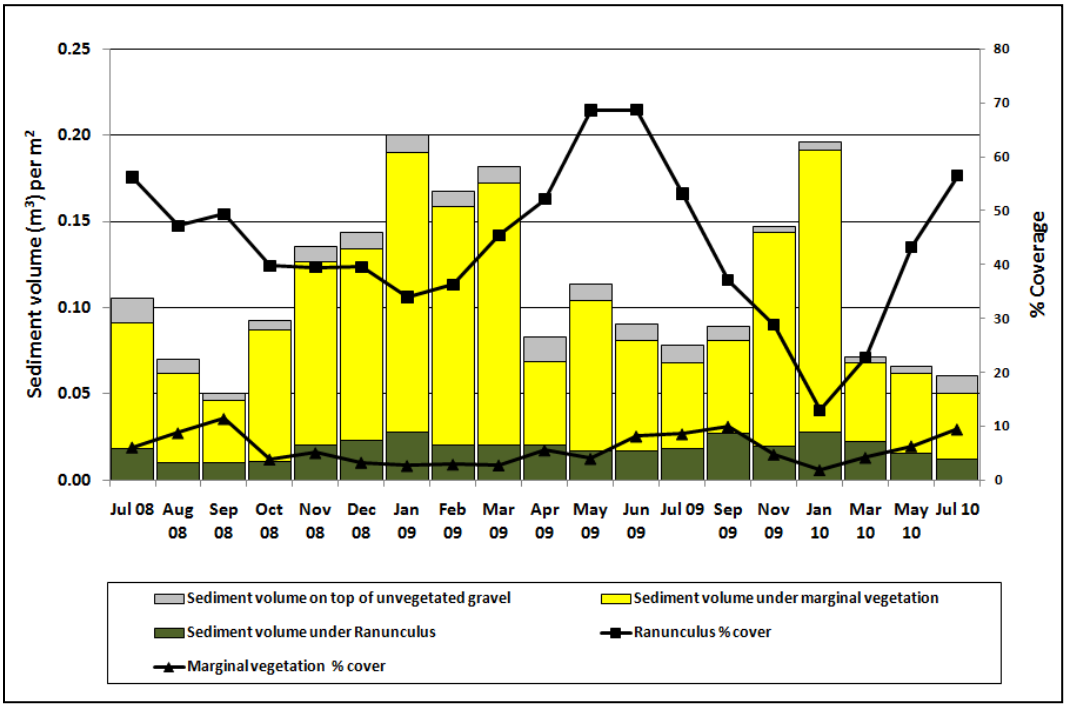


Figure 4.24 - The changes of fine sediment volume (m^3) per m^2 of *Ranunculus*, marginal vegetation and unvegetated gravel on the River Frome at Frome Vauchurch between July 2008 and July 2010.

The volume of fine sediment per m^2 of *Ranunculus* in January 2009 and January 2010 was 0.162 and 0.163 m^3 per m^2 respectively. The least volume of sediment per m^2 of *Ranunculus* at Frome Vauchurch was during September 2008 at 0.099 m^3 per m^2. Marginal vegetation on the River Frome possessed conspicuously greater values of sediment volume per m^2 than *Ranunculus* throughout the two year period. The greatest values of sediment volume per m^2 within the marginal vegetation were also found during January 2009 and January 2010 at 0.162 and 0.163 m^3 per m^2 respectively. In addition, the month with the least sediment volume per m^2 of marginal vegetation was during September 2008 at 0.036 m^3 per m^2, this coincided with the sediment volume per m^2 of *Ranunculus*.

4.1.7 Water velocity distribution

4.1.7.1 Bere Stream, July 2008 – July 2010

Spatial patterns of water flow were greatly influenced by the growth and die-back of three main macrophytes during the period of the surveys (See section 4.1.2 for growth and recession). The marginal areas of the stream generally experienced the lowest water flow velocities (Figure 4.25). Zones of low flow velocity in the margins were created by the colonisation and dominance of *Nasturtium* from August 2008 to March 2009, and also *Apium* between April 2008 and July 2009. The growth and dominance of the emergent *Ranunculus* within the centre of the channel between February and May 2009 also created mid-channel zones of low flow velocity. The increased growth of within channel aquatic macrophytes created areas with constricted high velocity flow which were unvegetated and possessed gravels that were free of surficial fine sediment. There were examples of how water flow became separated into two parallel 'pseudo-channels' of high velocity flow because of the increasing growth of emergent *Ranunculus* patches within the middle of the channel. This occurred in the channel from January to March 2009, and also from January and May 2010. There were also a few examples during the survey period where

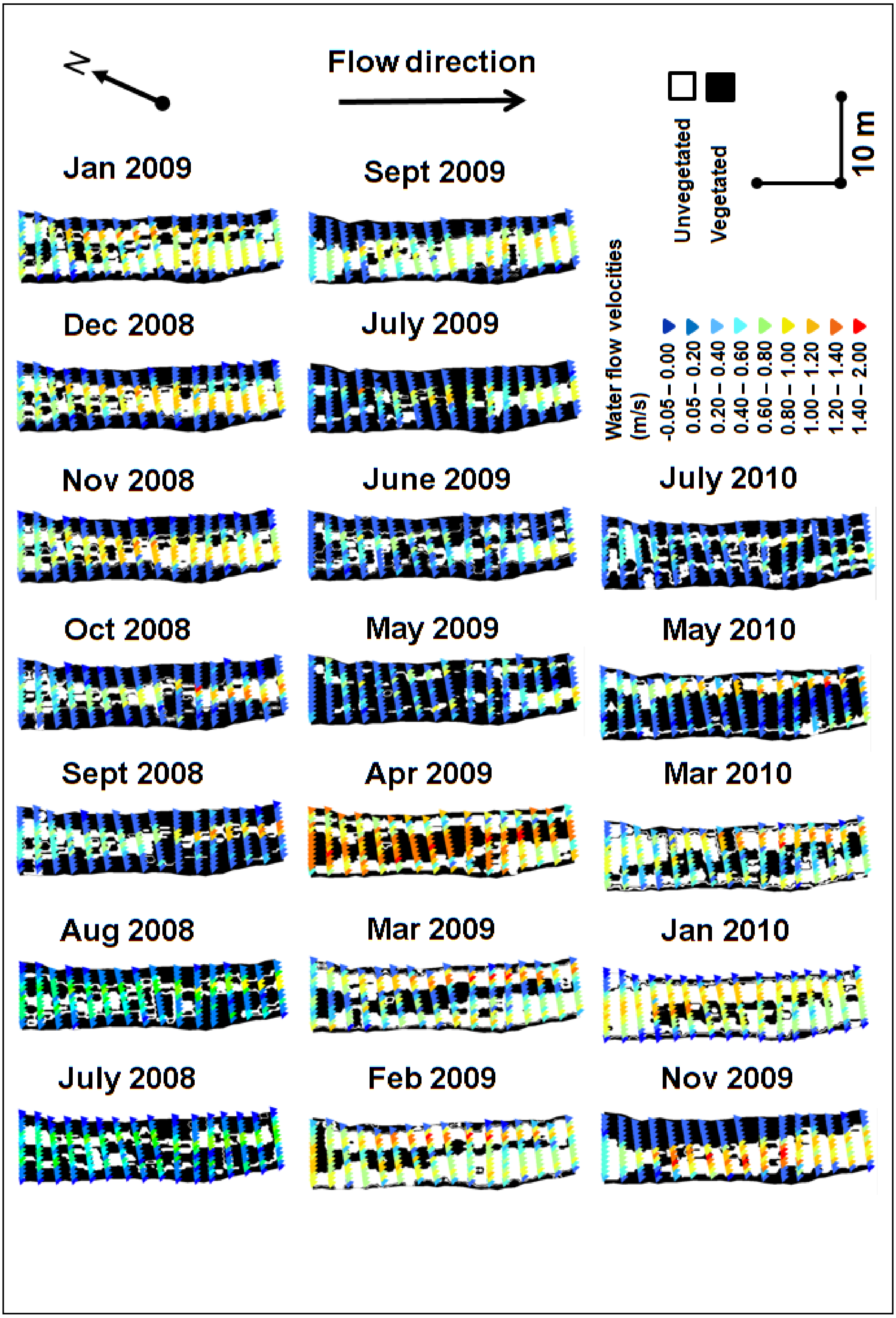


Figure 4.25 - The spatial and temporal changes of mean water flow velocities (m s^{-1}) taken at the 0.6 D in relation to corresponding changes of in-channel vegetation on the Bere Stream at Snatford Bridge between July 2008 and July 2010.

constricted high velocity water flow had created potential conditions erosion of the channel bank behind stable vegetated beds by directing smaller channels away from the main flow channel. Examples of possible anastomosis processes were observed within the marginal beds of *Nasturtium* near the right bank from August 2008 to October 2008, and beds of *Apium* on the left bank (Figure 4.26).

Figure 4.26 – An example of bank erosion by *Apium nodiflorum* on the left bank of Bere Stream at Snatford Bridge in March 2010. Water flowing with high velocity is forced around the patch of *Apium*, causing undercutting of the river bank. Picture taken by G. Davies.

4.1.7.2 Frome Vauchurch, July 2008 –July 2010

At the Frome Vauchurch site water flow velocities followed a dissimilar pattern to that of the Bere Stream throughout the annual cycle and seemingly regardless of macrophyte cover (Figure 4.27). Flow velocities tended to be evenly distributed across the channel width from transect 30, the most upstream transect, to transect 20.

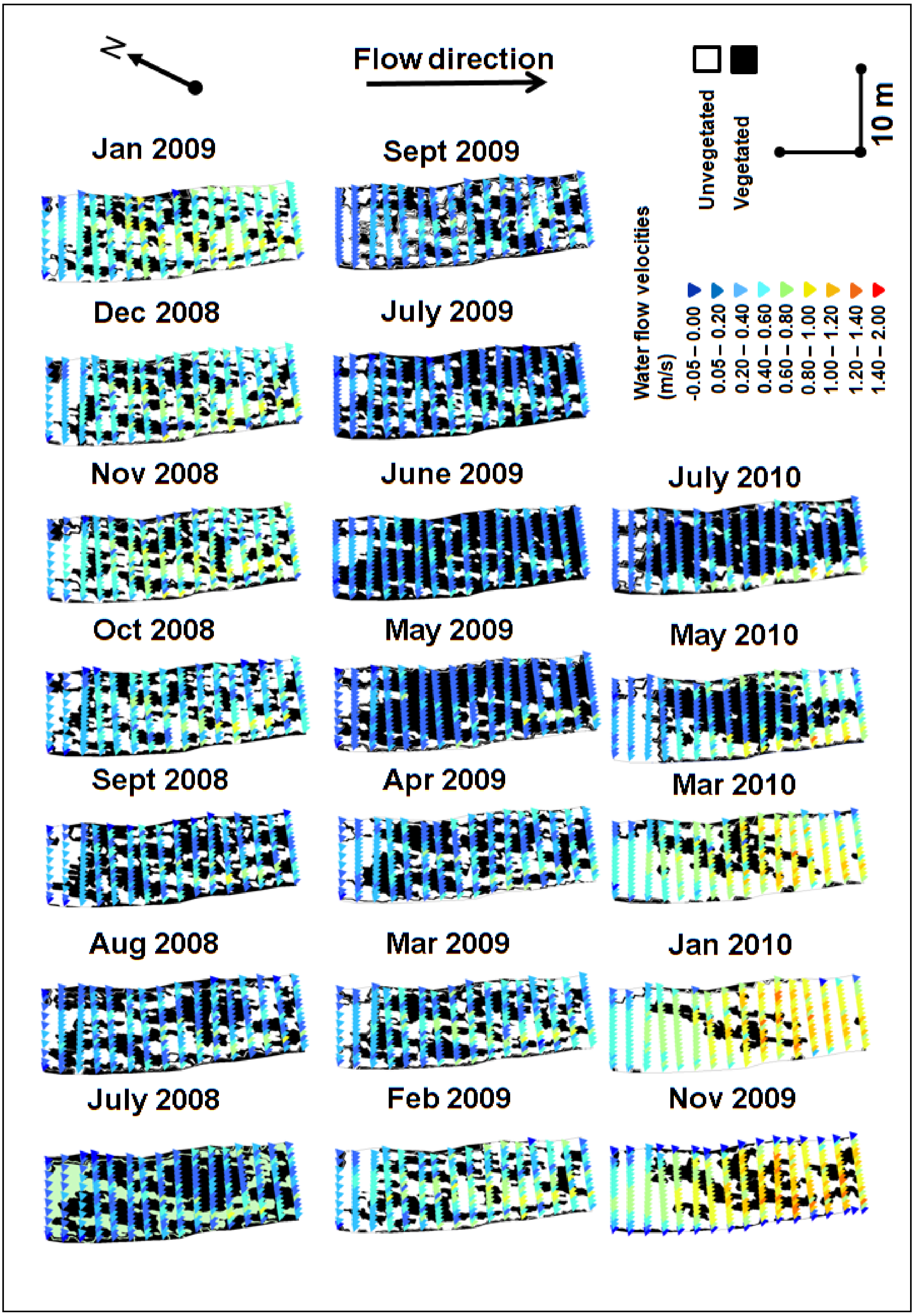


Figure 4.27 - The spatial and temporal changes of mean water flow velocities (m s^{-1}) taken at the 0.6 D in relation to corresponding changes of in-channel vegetation on the River Frome at Frome Vauchurch between July 2008 and July 2010.

Higher flow velocities tended to be constricted to the right bank throughout the two year survey period. The orientation of the thalweg did not change in course or shape throughout the study period apart from April 2008 to September 2009. During this period there appeared to be evenly distributed flow velocities across the entire channel cross-section, and also longitudinally from the most upstream transect (30) to the most downstream transect (0). During the surveys within those months it became very difficult to detect the position of the thalweg within the channel.

There were some seasonal variations in flow velocity within the channel that were evident between summer and winter periods. In the months from November 2008 to February 2009 and November 2009 to March 2010 there were greater flow velocities within the channel in comparison to that of the previous and following summer-autumn and spring-summer months respectively. The high flow velocities during the winter months also coincided with decreasing cover of *Ranunculus* within the channel during these periods.

4.1.8 River Discharge

River stage was measured continuously on both study reaches from 4 February 2009 to 21 July 2010 to describe the hydrological characteristics at each study site. Monitoring stage was also beneficial for assessing the impact of stage and discharge on sediment transport conditions at the time of each seasonal analogue release between February 2009 and July 2010. Measurements of stage were converted into discharge using a rating curve. Rating curves were constructed from the stage measurements in addition to corresponding calculations of discharge from survey measurements recorded during reach scale surveys. A measure of channel discharge was taken from the most upstream unvegetated transect, to ensure there was as little impact as possible by the seasonal growth of in-channel macrophytes.

4.1.8.1 Temporal changes of discharge on the Bere Stream

Figure 4.28 is the hydrograph illustrating the change in mean daily discharge on the Bere Stream during the period between February 2008 and July 2010. There is a distinct cyclical seasonal pattern in the hydrograph for the Bere Stream, as highlighted by other previous studies (Dawson, 1981; Wharton *et al*., 2006), where the discharge was higher between the late autumn to spring months due to the frequency of winter spates and the re-charge of the chalk aquifer. Discharge then gradually declined to a near-constant low level in the summer possibly due to the limited recharge through the summer months. The highest mean daily discharge during the measurement period was 2.37 m^3 s^{-1} on 4 December 2009, whilst the lowest value was 0.23 m^3 s^{-1} on the 10 October 2009.

During the measured period there were a number of atypical spikes indicating events in discharge that occurred during the summer months. One of the most notable being on the 8 August 2009 (2.31 m^3 s^{-1}), heavy rainfall during this period led to increased discharge. A number of other spikes in the hydrograph also indicate the presence of spates during the autumn and winter periods where higher levels of discharge are more common. An example is the period in the hydrograph between the 2 and 7 December 2009, which indicates high discharge levels can also occur during the winter recharge period.

A notable event occurred between 9 to the 23 August 2009 where the level of the discharge decreased dramatically and increased subsequently after. The most likely reason for why this event occurred was the build up of aquatic vegetation against the road bridge intersecting the stream. The gradual build-up serves to 'back-up' the water flow through the reach, and therefore artificially increasing the stage and discharge. The actual discharge within the channel was lower than what was actually recorded. The resulting mean daily level on the 11 August 2009 after the previous spate was 0.14 m, which was a 0.06 m difference to the last mean daily stage level recorded on the 5 August 2009.

The hydrograph also reveals the lack of variability in the daily discharge level recorded each day within the spring to summer months. This suggests that water flow through the reach was generally stable and not variable on a daily basis throughout

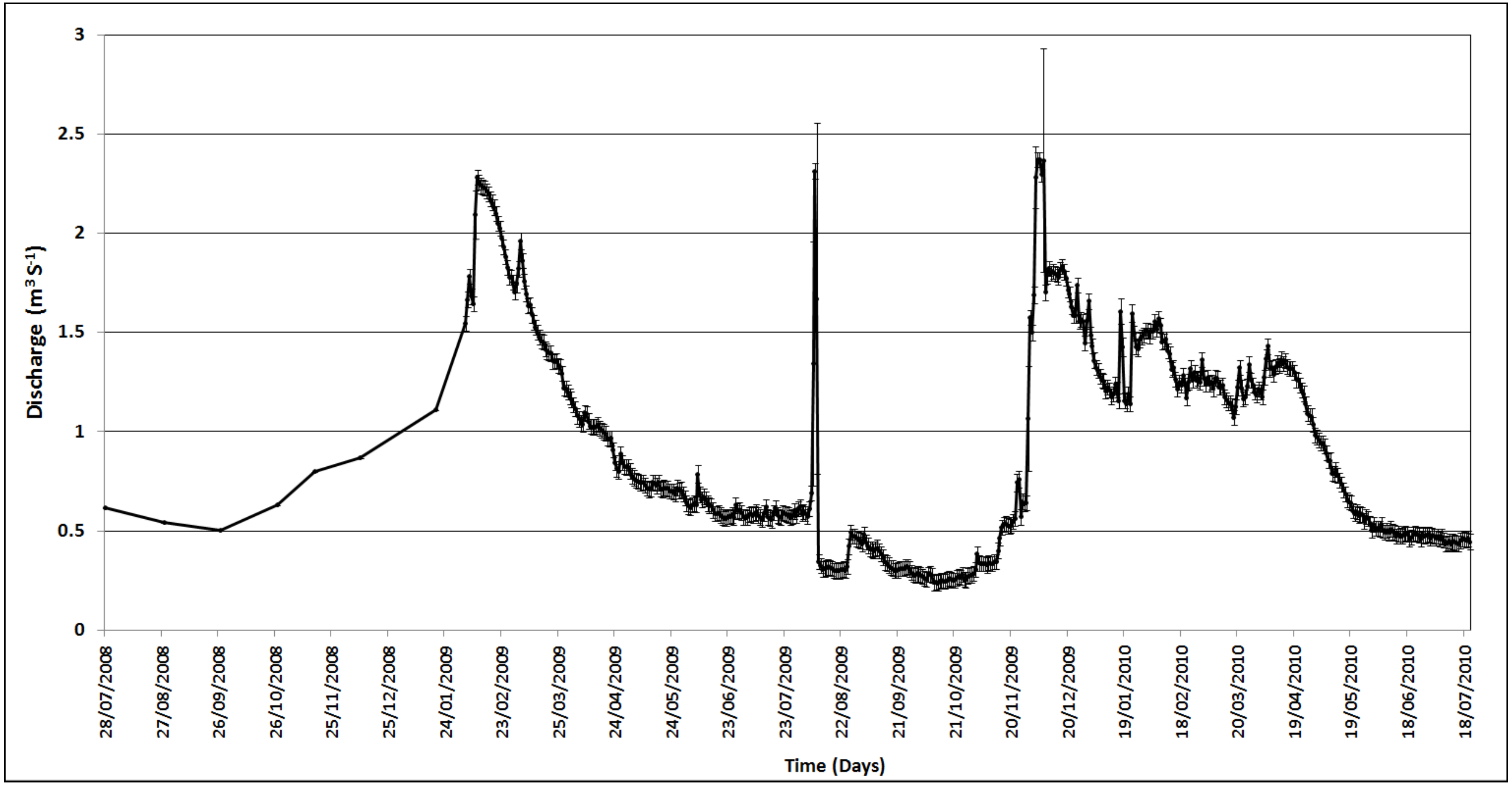


Figure 4.28 – The hydrograph illustrating changes in mean daily discharge (whiskers indicate standard deviation) at Snatford Bridge on the Bere Stream. Monthly discharge measurements from 28 July 2008 to 19 January 2009 are estimates of discharge from survey measurements. Measurements of mean daily discharge from 4 February 2009 until 21 July 2010 are estimated from stage measurements recorded in 15 minute intervals.

the spring-summer periods. In the autumn-winter periods on the hydrograph it was typical that there were higher variations in daily recorded discharge. One of the most notable was on 7 December 2009, which had a mean discharge of 2.37 ± 0.56 (SD) $m^3 s^{-1}$.

4.1.8.2 Temporal changes of discharge on the River Frome

The shape of the hydrograph from Frome Vauchurch indicates that there were seasonal changes in channel discharge (Figure 4.29). A longterm trend of decreasing discharge was determined over the period from 4 February 2009 to the 19 October 2009. This was followed by a rapid succession of erratic changes in discharge during the autumn and winter period of 2009. Autumn and winter months tended to experience regular rapid changes in discharge, compared with spring or summer months. The highest and lowest values of discharge within the gauged period were 2.95 and 0.68 $m^3 s^{-1}$ on 5 August 2009 and 17 October 2010 respectively.

Throughout the entire measured period there was evidence of 'flashy' hydrology in this section of the River Frome. The general seasonal pattern of the entire hydrograph is punctuated by regular minor events and spates, where daily discharge values were noticeably variable. The flashy nature of the channel hydrology was most likely influenced by additional discharge from the River Hooke, the River Hooke-River Frome confluence is less than one mile upstream from the study site. The River Hooke drains from a different part of the Frome catchment (Bowes *et al*., 2005). In between periods of spate there are general conditions of decreasing mean daily stage level with low daily variability in stage level on individual 24 hour periods. These periods in the hydrograph represent the gradual draining of temporary water stored within the chalk aquifer after a significant recharge period (Sear *et al*., 1999). A clear example of this was represented by the period between 8 August 2009 and 3 October 2009. This occurred subsequent to a large rainfall event, which coincided with the same period as that described on the Bere Stream. Periods of heavy rainfall created large events relating to discharge which are clearly visible on the hydrograph. The most notable example is that which occurred during the summer period of 2009 between the 1 and 8 August 2009.

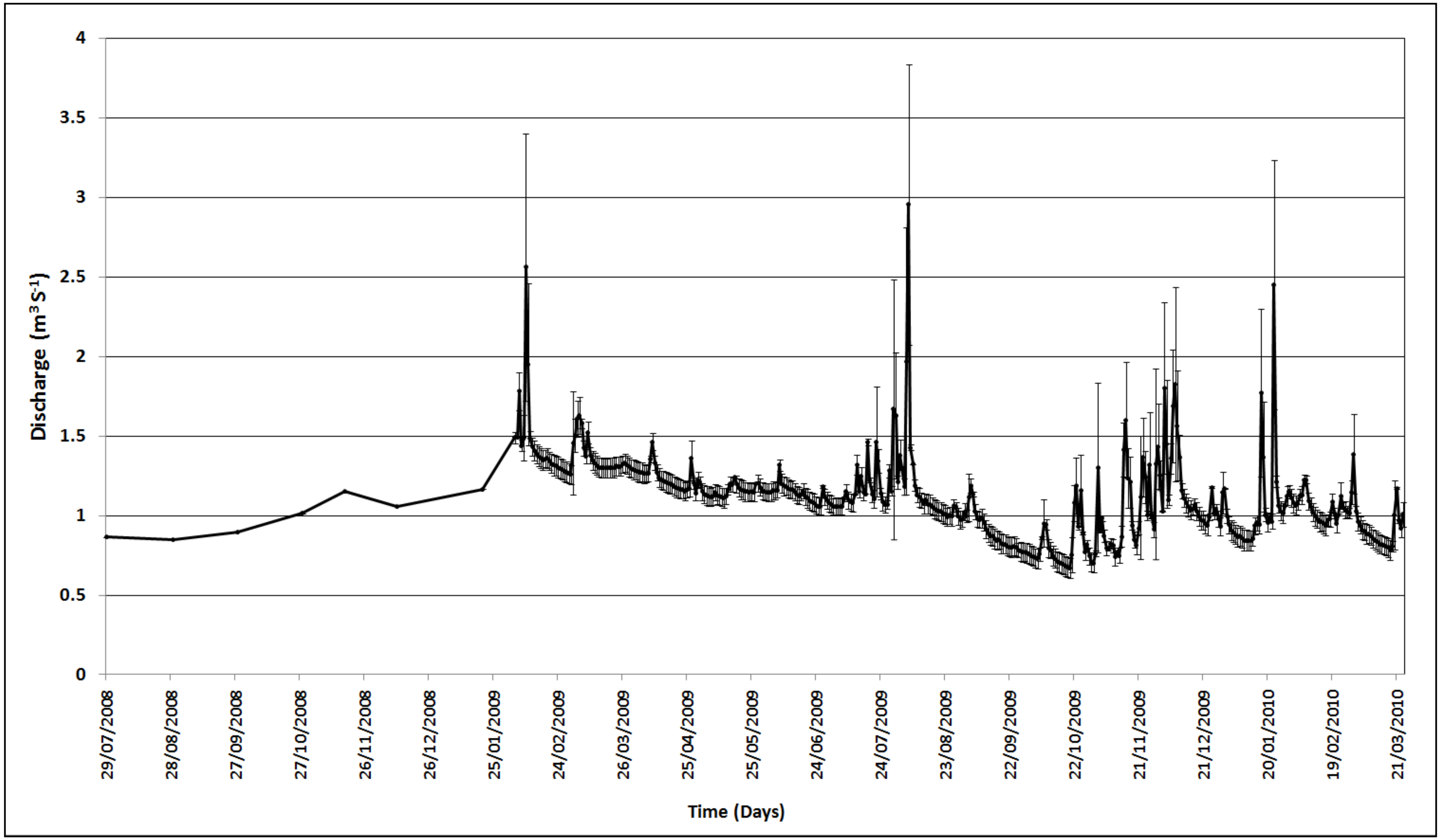


Figure 4. 29 - The hydrograph illustrating changes in mean daily discharge (whiskers indicate standard deviation) at Frome Vauchurch on the River Frome. Monthly discharge measurements from 29 July 2008 to 20 January 2009 are estimates of discharge from survey measurements. Measurements of mean daily discharge from 4 February 2009 until 21 July 2010 are estimated from stage measurements recorded in 15 minute intervals.

4.1.9 Statistical analyses of field survey datasets

Using the collected survey data it was possible to further investigate differences in sediment depth, water velocity and total depth within the two study reaches between all the months surveyed from July 2008 to July 2010. It was also possible to further explore whether there were any significant differences in sediment depth, water velocity and total water depth between emergent and submergent *Ranunculus* patches at both sites, and between *Ranunculus* and *Nasturtium* patches within the Bere Stream.

Datasets were initially tested for normality using a Kolmogorov-Smirnov normality test where the number of samples within a dataset were >20. An Anderson-Darling normality test was used where the number of samples within a dataset were <20. A series of Kruskal-Wallis tests were used to determine significant differences between samples.

4.1.9.1 Statistical analyses of Bere Stream reach survey datasets

Data in Table 4.1 illustrate the results of the statistical tests for the July 2008 to July 2010 survey period on the Bere Stream study reach.

Throughout the study period there remained a highly significant difference (***P*** <0.001) in the depth of sediment within open and vegetated areas of the reach. Open areas tended to exhibit little or no sediment deposition in comparison to areas covered by vegetation, 0.005 ± 0.003 (SD) and 0.03 ± 0.01 (SD) m respectively. Water flow velocities within open and vegetated areas of the reach were also highly significantly different (***P*** <0.002) for all months between July 2008 and July 2010. Vegetated areas of the reach displayed much reduced water flow velocities (0.269 ± 0.105 (SD) m s^{-1}) compared with that of open areas (0.636 ± 0.126 (SD) m s^{-1}).

Total water depth measurements taken within open and vegetated areas were also analysed for significant differences. All months apart from April 2009 (***P*** = 0.12) indicated there was a highly significant difference (***P*** <0.001) between the total depth of open and vegetated areas within the reach, 0.32 ± 0.05 (SD) and 0.26 ± 0.05 (SD) m respectively. The lack of significant difference in total water depth values between open and vegetated areas of the reach in April 2009 coincided with the lowest

Table 4.1 - A table of mean values (±SD) for sediment depth (cm), total depth (m) and water flow velocities (m s^{-1}) from open (free from vegetation) and vegetated areas on the Bere Stream at Snatford Bridge. The *P*-values illustrate the results of Kruskal-Wallis one-way tests to analyse whether significant differences were present between open and vegetated areas of the reach for each parameter. The resulting *P*-values that are bold indicate a significant result. OSD – Sediment depth in open areas, VSD –Sediment depth in vegetated areas, OTD – Total depth in open areas, VTD – Total depth in vegetated areas, OWV – Water flow velocities within open areas and VWV – Water flow velocities within vegetated areas. There was one degree of freedom within each ANOVA test as only two groups were tested.

Month	Mean sediment depth				Mean total depth				Mean water velocities			
	OSD (cm)	VSD (cm)	*P* (OSD vs VSD)	d.f.	OTD (m)	VTD (m)	*P* (OTD vs VTD)	d.f.	OWV (m/s)	VWV (m/s)	*P* (OWV vs VWV)	d.f.
Jul 08	1.0 ± 2.2	3.6 ± 4.8	**<0.001**	**1**	0.30 ± 0.05	0.24 ± 0.09	**<0.001**	**1**	0.511 ± 0.273	0.206 ± 0.251	**<0.001**	**1**
Aug 08	0.8 ± 2.0	4.0 ± 4.5	**<0.001**	**1**	0.30 ± 0.05	0.24 ± 0.08	**<0.001**	**1**	0.494 ± 0.285	0.233 ± 0.280	**<0.001**	**1**
Sep 08	0.4 ± 1.5	2.7 ± 3.5	**<0.001**	**1**	0.35 ± 0.06	0.28 ± 0.08	**<0.001**	**1**	0.592 ± 0.328	0.221 ± 0.275	**<0.001**	**1**
Oct 08	0.5 ± 1.1	2.7 ± 3.2	**<0.001**	**1**	0.35 ± 0.06	0.28 ± 0.09	**<0.001**	**1**	0.619 ± 0.382	0.204 ± 0.271	**<0.001**	**1**
Nov 08	0.3 ± 1.7	3.3 ± 4.0	**<0.001**	**1**	0.34 ± 0.05	0.26 ± 0.09	**<0.001**	**1**	0.832 ± 0.274	0.260 ± 0.315	**<0.001**	**1**
Dec 08	0.6 ± 2.5	3.5 ± 4.1	**<0.001**	**1**	0.34 ± 0.05	0.25 ± 0.09	**<0.001**	**1**	0.807 ± 0.286	0.296 ± 0.346	**<0.001**	**1**
Jan 09	0.2 ± 1.4	4.1 ± 4.9	**<0.001**	**1**	0.35 ± 0.06	0.27 ± 0.09	**<0.001**	**1**	0.730 ± 0.279	0.367 ± 0.351	**<0.001**	**1**
Feb 09	1.0 ± 4.0	5.0 ± 6.2	**<0.001**	**1**	0.42 ± 0.07	0.38 ± 0.31	**<0.001**	**1**	0.790 ± 0.298	0.545 ± 0.353	**<0.001**	**1**
Mar 09	0.5 ± 1.9	3.8 ± 5.1	**<0.001**	**1**	0.34 ± 0.07	0.29 ± 0.11	**<0.001**	**1**	0.725 ± 0.341	0.354 ± 0.336	**<0.001**	**1**
Apr 09	0.1 ± 0.9	3.4 ± 5.0	**<0.001**	**1**	0.30 ± 0.06	0.28 ± 0.09	0.12	**1**	0.610 ± 0.316	0.252 ± 0.259	**<0.001**	**1**
May 09	0.1 ± 0.8	3.0 ± 4.4	**<0.001**	**1**	0.31 ± 0.05	0.28 ± 0.09	**<0.001**	**1**	0.509 ± 0.260	0.204 ± 0.215	**<0.001**	**1**
Jun 09	0.4 ± 1.6	2.8 ± 4.4	**<0.001**	**1**	0.29 ± 0.05	0.24 ± 0.09	**<0.001**	**1**	0.485 ± 0.249	0.178 ± 0.197	**<0.001**	**1**
Jul 09	0.3 ± 1.0	2.4 ± 3.7	**<0.001**	**1**	0.29 ± 0.06	0.23 ± 0.08	**<0.001**	**1**	0.483 ± 0.312	0.210 ± 0.273	**<0.001**	**1**
Sep 09	0.2 ± 0.8	3.2 ± 3.2	**<0.001**	**1**	0.20 ± 0.05	0.14 ± 0.06	**<0.001**	**1**	0.639 ± 0.255	0.150 ± 0.271	**<0.001**	**1**
Nov 09	0.1 ± 0.6	3.3 ± 4.1	**<0.001**	**1**	0.30 ± 0.06	0.23 ± 0.08	**<0.001**	**1**	0.829 ± 0.340	0.255 ± 0.402	**<0.001**	**1**
Jan 10	0.7 ± 2.6	4.4 ± 5.2	**<0.001**	**1**	0.35 ± 0.07	0.24 ± 0.10	**<0.001**	**1**	0.724 ± 0.307	0.323 ± 0.412	**<0.001**	**1**
Mar 10	0.6 ± 2.7	3.6 ± 5.0	**<0.001**	**1**	0.32 ± 0.07	0.25 ± 0.09	**<0.001**	**1**	0.647 ± 0.351	0.483 ± 0.319	**0.002**	**1**
May 10	0.5 ± 2.6	3.0 ± 4.6	**<0.001**	**1**	0.31 ± 0.06	0.26 ± 0.10	**<0.001**	**1**	0.590 ± 0.369	0.181 ± 0.270	**<0.001**	**1**
Jul 10	0.5 ± 1.3	2.7 ± 4.4	**<0.001**	**1**	0.30 ± 0.07	0.25 ± 0.09	**<0.001**	**1**	0.465 ± 0.218	0.181 ± 0.186	**<0.001**	**1**

cover of *Nasturtium* within the whole survey period (3 %, see section 4.1.2). This possibly suggests that the total depth of all macrophytes within April 2009 was near equivalent to the total depth of open areas of the reach, when compared to all of the other months surveyed during the two year period.

4.1.9.2 Sediment depth within *Ranunculus* & *Nasturtium* on the Bere Stream

Further statistical tests were used to confirm whether there was a significant difference between *Ranunculus* and *Nasturtium* in relation to the depth of sediment within patches. Initial mean values of sediment depth from *Ranunculus* and *Nasturtium* at 2.3 ± 0.8 (SD) and 4.2 ± 1.8 (SD) cm respectively indicate there may be some differences between the two types of macrophyte. The results in Table 4.2 suggest that the depth of sediment within beds of *Ranunculus* and *Nasturtium* were significantly different (***P*** <0.05) in all months apart from July 2008, November 2008, December 2008, June 2009, July 2009 and January 2010. There appeared to be a seasonal pattern in the months where there was no significant difference between *Ranunculus* and *Nasturtium* patches in relation to sediment depth. In May 2010 there was not enough measurement points recorded within *Nasturtium* for sufficient statistical analyses to be conducted.

Ranunculus and *Nasturtium* were nearly equal in cover during July 2008 at 24 and 19 % respectively, and July 2009 at 22 and 24 % respectively. However in November 2008, December 2008 and June 2009 the coverage of *Ranunculus* and *Nasturtium* was very different (See Section 4.1.2).

4.1.9.3 Sediment depth within patches of emergent and submergent *Ranunculus* on the Bere Stream

Measurements of sediment depth recorded within *Ranunculus* during the two year survey on the Bere Stream were further categorised as those from emergent and those from submergent *Ranunculus*. The mean sediment depth recorded within submergent

Table 4.2 – A table of the monthly mean values (± **SD)** for NSD – *Nasturtium* sediment depth (cm), RSD – *Ranunculus* sediment depth (cm), NWV – *Nasturtium* water flow velocities (m s^{-1}), RWV – *Ranunculus* water flow velocities (m s^{-1}), ESD – Sediment depth (cm) within emergent *Ranunculus*, SSD – Sediment depth (cm) within submergent *Ranunculus*, EWV – Water flow velocities (m s^{-1}) within emergent *Ranunculus* and SWV – Water flow velocities (m s^{-1}) within submergent *Ranunculus*. The ***P***-values are the result of Kruskal-Wallis statistical tests to determine whether a significant difference is present between the paired groups, with significant values highlighted in bold.

Months	Sediment depth (cm)				Water flow velcoities (m/s)			
	NSD	RSD	*P* (NSD vs RSD)	d.f.	NWV	RWV	*P* (NWV vs RWV)	d.f.
Jul 08	4.3 ± 5.2	3.2 ± 3.7	0.39	1	0.108 ± 0.151	0.384 ± 0.278	**<0.001**	1
Aug 08	4.3 ± 4.7	2.1 ± 2.8	**<0.001**	1	0.123 ± 0.162	0.531 ± 0.331	**<0.001**	1
Sep 08	2.9 ± 3.8	1.2 ± 1.9	**0.001**	1	0.121 ± 0.159	0.652 ± 0.263	**<0.001**	1
Oct 08	2.9 ± 3.3	1.6 ± 2.1	**0.002**	1	0.113 ± 0.152	0.626 ± 0.284	**<0.001**	1
Nov 08	3.5 ± 4.4	2.7 ± 2.9	0.32	1	0.097 ± 0.133	0.698 ± 0.248	**<0.001**	1
Dec 08	3.4 ± 4.1	3.9 ± 4.3	0.81	1	0.080 ± 0.067	0.713 ± 0.275	**<0.001**	1
Jan 09	4.3 ± 5.2	3.3 ± 4.4	**0.04**	1	0.085 ± 0.128	0.631 ± 0.271	**<0.001**	1
Feb 09	7.4 ± 6.7	3.8 ± 5.5	**<0.001**	1	0.087 ± 0.077	0.662 ± 0.297	**<0.001**	1
Mar 09	5.0 ± 5.7	3.1 ± 4.9	**0.02**	1	0.080 ± 0.057	0.406 ± 0.342	**<0.001**	1
Apr 09	5.5 ± 6.2	2.1 ± 3.7	**0.008**	1	0.189 ± 0.169	0.245 ± 0.261	0.96	1
May 09	3.3 ± 3.1	2.0 ± 3.3	**0.006**	1	0.086 ± 0.093	0.221 ± 0.237	**0.02**	1
Jun 09	3.3 ± 5.0	2.2 ± 3.5	**0.33**	1	0.136 ± 0.108	0.272 ± 0.262	0.19	1
Jul 09	2.8 ± 4.7	1.8 ± 2.6	0.32	1	0.116 ± 0.148	0.464 ± 0.340	**<0.001**	1
Sep 09	3.5 ± 3.6	1.9 ± 2.5	**0.02**	1	0.057 ± 0.096	0.740 ± 0.179	**<0.001**	1
Nov 09	3.8 ± 5.0	1.9 ± 2.7	**0.03**	1	0.104 ± 0.072	1.114 ± 0.313	**<0.001**	1
Jan 10	3.2 ± 4.0	1.8 ± 3.6	0.35	1	0.125 ± 0.117	0.818 ± 0.275	**<0.001**	1
Mar 10	9.6 ± 5.9	1.6 ± 2.8	**<0.001**	1	-0.029 ± 0.023	0.504 ± 0.254	N/A	-
May 10	2.0 ± 4.0	1.8 ± 2.9	N/A	-	0.189 ± 0.178	0.186 ± 0.282	N/A	-
Jul 10	2.8 ± 3.9	1.5 ± 2.3	**0.04**	1	0.108 ± 0.048	0.273 ± 0.224	**0.01**	1

Months	Sediment depth (cm)				Water flow velocities (m/s)			
	ESD	SSD	(*P* ESD vs SSD)	d.f.	EWV	SWV	*P* (EWV vs SWV)	d.f.
Jul 08	N/A ± N/A	3.2 ± 3.7	N/A	-	0.384 ± 0.275	N/A ± N/A	N/A	-
Aug 08	2.8 ± 2.6	1.9 ± 3.1	0.34	1	0.142 ± 0.136	0.632 ± 0.283	**<0.001**	1
Sep 08	N/A ± N/A	1.2 ± 1.9	N/A	-	N/A ± N/A	0.652 ± 0.257	N/A	-
Oct 08	1.6 ± 2.1	N/A ± N/A	N/A	-	0.626 ± 0.278	N/A ± N/A	N/A	-
Nov 08	3.1 ± 3.0	2.6 ± 2.4	0.29	1	0.551 ± 0.264	0.756 ± 0.208	**0.04**	1
Dec 08	4.8 ± 4.1	2.7 ± 4.1	**0.019**	1	0.820 ± 0.285	0.651 ± 0.242	0.09	1
Jan 09	4.4 ± 4.7	2.6 ± 4.9	**0.008**	1	0.550 ± 0.235	0.679 ± 0.297	0.09	1
Feb 09	4.4 ± 5.4	3.3 ± 5.6	0.39	1	0.524 ± 0.255	0.818 ± 0.255	**<0.001**	1
Mar 09	3.7 ± 3.5	1.4 ± 5.2	**0.001**	1	0.331 ± 0.276	0.638 ± 0.407	**<0.001**	1
Apr 09	2.5 ± 2.3	1.0 ± 4.0	**0.002**	1	0.159 ± 0.174	0.509 ± 0.305	**<0.001**	1
May 09	2.0 ± 2.9	2.1 ± 3.4	0.42	1	0.222 ± 0.279	0.362 ± 0.276	0.07	1
Jun 09	2.2 ± 3.8	2.5 ± 3.5	0.72	1	0.190 ± 0.200	0.593 ± 0.229	**<0.001**	1
Jul 09	2.0 ± 1.4	1.2 ± 3.2	0.91	1	0.398 ± 0.308	0.618 ± 0.363	0.06	1
Sep 09	6.0 ± 2.4	1.7 ± 0.0	N/A	-	0.496 ± 0.000	0.764 ± 0.160	N/A	-
Nov 09	2.0 ± 2.8	1.9 ± 1.4	N/A	-	N/A ± N/A	1.114 ± 0.313	N/A	-
Jan 10	N/A ± N/A	1.8 ± 3.6	N/A	-	N/A ± N/A	0.818 ± 0.275	N/A	-
Mar 10	2.4 ± 1.9	0.6 ± 3.1	**<0.001**	1	0.412 ± 0.180	0.587 ± 0.276	**0.013**	1
May 10	0.4 ± 3.0	1.9 ± 0.9	**0.03**	1	0.696 ± 0.438	0.166 ± 0.258	1.0	1
Jul 10	1.5 ± 1.2	0.9 ± 2.4	0.48	1	0.234 ± 0.197	0.554 ± 0.209	**<0.001**	1

patches was noticeably less in comparison with the sediment depth measured within emergent patches, at 1.8 ± 3.3 (SD) and 2.7 ± 4.0 (SD) cm correspondingly. Both datasets were considered non-normally distributed (***P*** <0.05) when tested with a Kolmogorov-Smirnov test. A subsequent Kruskal-Wallis one way test determined that there was a highly significant difference (***P*** <0.001) between patches of submergent and emergent *Ranunculus* in their values of sediment depth. Significant differences (***P*** <0.05) in the fine sediment depth between emergent and submergent *Ranunculus* were found in December 2008, January 2009, March 2009, April 2009, March 2010 and May 2010 (Table 4.2).

4.1.9.4 Water flow velocities within *Ranunculus* & *Nasturtium* at Bere Stream

During the July 2008-July 2010 study period there were highly significant differences (***P*** <0.02) in water flow velocities between *Ranunculus* and *Nasturtium* in the majority of the sample months. *Ranunculus* patches were characterised as having higher flow velocities within their patches (0.534 ± 0.242 (SD) m s^{-1}) compared to that of *Nasturtium* patches (0.104 ± 0.046 (SD) m s^{-1}). However, in April and June 2009 there were no significant differences in water flow velocities between *Ranunculus* and *Nasturtium* patches (***P*** >0.05, Table 4.2).

4.1.9.5 Water flow velocities within patches of emergent and submergent *Ranunculus* on the Bere Stream

All measurements of water flow velocities recorded within *Ranunculus* during the two year survey on the Bere Stream were further categorised as those from emergent and those from submergent *Ranunculus*. Mean water velocities within submergent *Ranunculus* patches was greater than that of the emergent patches at 0.561 ± 0.368 (SD) and 0.323 ± 0.282 (SD) m s^{-1} respectively. Both datasets were considered to be non-normally distributed (***P*** <0.05) by a Kolmogorov-Smirnov test. A subsequent Kruskal-Wallis test determined that there was a highly significant difference (***P*** <0.001) between all water velocity values recorded within patches of submergent *Ranunculus* and those within emergent *Ranunculus*. Within the majority of survey months there were significant differences (***P*** <0.05) between the water flow velocities within emergent and submergent *Ranunculus* (Table 4.2).

4.1.9.6 Statistical analyses of Frome Vauchurch reach survey datasets

Statistical tests were used to further investigate whether there were any significant differences in sediment depth, water velocity and total water depth between *Ranunculus* and open unvegetated areas within the Frome Vauchurch reach during the survey period from July 2008 to July 2010. The results of the statistical analyses on reach data are illustrated in Table 4.3.

Within the majority of the months between July 2008 and July 2010 there was a highly significant difference (***P*** <0.003) between vegetated and open areas of the study reach relating to sediment depth (Table 4.3). The majority of the gravel-bed was not smothered by surficial fine sediment within all survey months, with the exclusion of the upstream left bank margin. Most fine sediment storage occurred within marginal vegetated areas and *Ranunculus* patches (3.2 ± 1.4 (SD) cm) in comparison to open areas of the reach (1.0 ± 0.7 (SD) cm). This was similar to the observations made in the Bere Stream reach over the same survey period (see above). August 2008 and July 2010 were the only months during the survey period where sediment depth of vegetated patches and open areas was similar at ***P*** = 0.07 and ***P*** = 0.21 correspondingly. The total water depth within vegetated and open areas of the reach was significantly different (***P*** <0.01) for all months during the two year survey except in July 2010 (***P*** = 0.10). This infers that *Ranunculus* and marginal vegetation were frequently distributed in areas of shallower water depth (0.38 ± 0.07 (SD) m). In comparison open areas of the channel, for example between plant patches, tended to be deeper (0.42 ± 0.07 (SD) m).

Within the majority of months between July 2008 and July 2010 there were statistically significant differences in water flow velocities (***P*** <0.03) that occurred between vegetated (0.359 ± 0.225 (SD) m s^{-1}) and open areas (0.432 ± 0.170 (SD) m s^{-1}) of the reach. The months of November 2008 through to February 2009 in addition to November 2009 and March 2010 showed no significant difference (***P*** >0.05) in water flow velocities between vegetated and open areas. This suggests that water flow velocities were similar between vegetated and open areas of the channel during the autumn and winter months within the surveyed period.

Table 4.3 - A table of mean values (±SD) for sediment depth (cm), total depth (m) and water flow velocities (m s^{-1}) from open (free from vegetation) and vegetated areas on the River Frome at Frome Vauchurch. The *P*-values illustrate the results of Kruskal-Wallis one-way tests to analyse whether significant differences were present between open and vegetated areas of the reach for each parameter. The resulting *P*-values that are bold indicate a significant result. OSD – Sediment depth in open areas, VSD –Sediment depth in vegetated areas, OTD – Total depth in open areas, VTD – Total depth in vegetated areas, OWV – Water flow velocities within open areas and VWV – Water flow velocities within vegetated areas

Month	Mean sediment depth				Mean total depth				Mean water velocities			
	OSD (cm)	VSD (cm)	*P* (OSD vs VSD)	d.f.	OTD (m)	VTD (m)	*P* (OTD vs VTD)	d.f.	OWV (m/s)	VWV (m/s)	*P* (OWV vs VWV)	d.f.
Jul 08	1.6 ± 2.0	2.6 ± 4.2	**0.003**	**1**	0.39 ± 0.12	0.33 ± 0.11	**<0.001**	**1**	0.253 ± 0.181	0.211 ± 0.179	**0.03**	**1**
Aug 08	1.1 ± 1.8	2.0 ± 3.6	0.07	**1**	0.39 ± 0.11	0.32 ± 0.11	**<0.001**	**1**	0.315 ± 0.170	0.229 ± 0.177	**<0.001**	**1**
Sep 08	0.3 ± 0.9	2.4 ± 4.9	**<0.001**	**1**	0.40 ± 0.11	0.34 ± 0.12	**<0.001**	**1**	0.362 ± 0.163	0.238 ± 0.176	**<0.001**	**1**
Oct 08	0.3 ± 1.4	2.3 ± 5.5	**<0.001**	**1**	0.44 ± 0.11	0.39 ± 0.11	**<0.001**	**1**	0.413 ± 0.172	0.355 ± 0.186	**0.01**	**1**
Nov 08	0.8 ± 3.4	4.3 ± 7.4	**<0.001**	**1**	0.48 ± 0.13	0.45 ± 0.11	**0.01**	**1**	0.538 ± 0.179	0.515 ± 0.207	0.32	**1**
Dec 08	0.7 ± 3.1	3.4 ± 5.9	**<0.001**	**1**	0.44 ± 0.13	0.41 ± 0.11	**<0.001**	**1**	0.456 ± 0.180	0.412 ± 0.210	0.07	**1**
Jan 09	0.8 ± 3.4	4.3 ± 7.4	**<0.001**	**1**	0.48 ± 0.13	0.45 ± 0.11	**0.01**	**1**	0.538 ± 0.179	0.515 ± 0.207	0.32	**1**
Feb 09	3.3 ± 6.1	1.0 ± 4.0	**<0.001**	**1**	0.44 ± 0.12	0.49 ± 0.13	**<0.001**	**1**	0.433 ± 0.210	0.480 ± 0.195	0.06	**1**
Mar 09	1.2 ± 4.9	3.2 ± 6.2	**<0.001**	**1**	0.47 ± 0.13	0.43 ± 0.12	**<0.001**	**1**	0.398 ± 0.190	0.303 ± 0.205	**<0.001**	**1**
Apr 09	1.0 ± 3.7	2.9 ± 5.8	**<0.001**	**1**	0.52 ± 0.12	0.47 ± 0.12	**<0.001**	**1**	0.345 ± 0.174	0.228 ± 0.176	**<0.001**	**1**
May 09	0.8 ± 2.5	2.5 ± 4.8	**<0.001**	**1**	0.46 ± 0.13	0.41 ± 0.12	**<0.001**	**1**	0.238 ± 0.146	0.126 ± 0.136	**<0.001**	**1**
Jun 09	0.8 ± 2.3	2.7 ± 5.7	**<0.001**	**1**	0.52 ± 0.14	0.46 ± 0.12	**<0.001**	**1**	0.268 ± 0.135	0.178 ± 0.153	**<0.001**	**1**
Jul 09	1.0 ± 3.5	2.6 ± 4.3	**<0.001**	**1**	0.45 ± 0.11	0.39 ± 0.11	**<0.001**	**1**	0.253 ± 0.122	0.175 ± 0.161	**<0.001**	**1**
Sep 09	0.9 ± 2.6	3.7 ± 5.5	**<0.001**	**1**	0.32 ± 0.11	0.26 ± 0.11	**<0.001**	**1**	0.272 ± 0.154	0.161 ± 0.142	**<0.001**	**1**
Nov 09	0.6 ± 3.4	6.1 ± 8.1	**<0.001**	**1**	0.41 ± 0.12	0.34 ± 0.14	**<0.001**	**1**	0.801 ± 0.243	0.825 ± 0.338	0.11	**1**
Jan 10	0.8 ± 4.1	6.4 ± 8.8	**<0.001**	**1**	0.37 ± 0.13	0.34 ± 0.10	**0.03**	**1**	0.751 ± 0.242	0.866 ± 0.223	**0.01**	**1**
Mar 10	0.5 ± 2.9	4.2 ± 6.2	**<0.001**	**1**	0.36 ± 0.13	0.30 ± 0.12	**<0.001**	**1**	0.686 ± 0.252	0.634 ± 0.273	0.23	**1**
May 10	0.7 ± 3.6	2.5 ± 4.7	**<0.001**	**1**	0.27 ± 0.11	0.29 ± 0.11	**0.02**	**1**	0.517 ± 0.258	0.207 ± 0.192	**<0.001**	**1**
Jul 10	1.7 ± 4.4	1.6 ± 3.4	0.21	**1**	0.33 ± 0.14	0.30 ± 0.11	0.10	**1**	0.371 ± 0.251	0.165 ± 0.141	**<0.001**	**1**

4.1.9.7 Sediment depth within patches of emergent and submergent *Ranunculus* at Frome Vauchurch

Measurements of sediment depth recorded within *Ranunculus* at Frome Vauchurch during the two year survey were further categorised as those from emergent and submergent patches. The mean sediment depth recorded within submergent patches was greater than the mean sediment depth within emergent patches at 2.5 ± 3.7 (SD) and 2.0 ± 3.5 (SD) cm correspondingly. Both datasets were considered to be non-normally distributed from the result of a Kolmogorov-Smirnov test (***P*** <0.05). A subsequent Kruskal-Wallis test determined that there was a highly significant difference (***P*** <0.001) in sediment depth values measured between patches of submergent and emergent *Ranunculus*. Significant differences (***P*** <0.05) in fine sediment depth between emergent and submergent *Ranunculus* were found within some but not all of the summer months (Table 4.4).

4.1.9.8 Water flow velocities within patches of emergent and submergent *Ranunculus* at Frome Vauchurch

All water flow velocity measurements recorded within *Ranunculus* during the two year survey at Frome Vauchurch were further categorised as those from emergent and submergent *Ranunculus* patches. Values of mean water velocity within submergent *Ranunculus* patches were greater than that of the emergent patches at 0.397 ± 0.216 (SD) m $s^{-1}$and 0.219 ± 0.199 (SD) m s^{-1} correspondingly. Both datasets were considered non-normally distributed (***P*** <0.05) by a Kolmogorov-Smirnov test. A subsequent Kruskal-Wallis test determined that there was a highly significant difference (***P*** <0.001) between the water velocities recorded within patches of submergent and emergent *Ranunculus*. Additionally, there were significant differences (***P*** <0.05) between the water flow velocities within emergent and submergent *Ranunculus* patches in all survey months excluding August 2008, November 2008 and March 2010 (Table 4.4).

Table 4.4- A table of the monthly mean values (±SD) for Em SD – Sediment depth (cm) within emergent *Ranunculus*, Sub SD – Sediment depth (cm) within submergent *Ranunculus*, Em WV – Water flow velocities (m s^{-1}) within emergent *Ranunculus* and Sub WV – Water flow velocities (m s^{-1}) within submergent *Ranunculus* on the River Frome at Frome Vauchurch between July 2008 and July 2010. The *P*-values are a result of a series of Kruskal-Wallis one-way statistical tests to determine whether a significant difference is present between the paired groups, with significant values highlighted in bold. Months where no measurements were taken because a group was absent during the survey are marked with N/A. N/A is written in the *P*-value column when insufficient data values were collected to perform a statistical test.

	Sediment depth (cm)				Water flow velcoities (m/s)			
Month	**Em SD**	**Sub SD**	***P* (Em SD vs Sub SD)**	**d.f.**	**Em WV**	**Sub WV**	**Em (WV vs Sub WV)**	**d.f.**
Jul 08	1.7 ± 2.2	2.8 ± 2.6	**<0.001**	**1**	0.168 ± 0.170	0.292 ± 0.179	**<0.001**	**1**
Aug 08	1.0 ± 1.6	1.3 ± 2.1	0.08	**1**	0.224 ± 0.176	0.264 ± 0.186	0.16	**1**
Sep 08	1.2 ± 2.0	1.2 ± 1.9	0.99	**1**	0.181 ± 0.157	0.368 ± 0.147	**<0.001**	**1**
Oct 08	1.2 ± 2.0	1.4 ± 2.0	0.21	**1**	0.320 ± 0.162	0.462 ± 0.191	**<0.001**	**1**
Nov 08	2.4 ± 3.5	2.8 ± 3.9	0.83	**1**	0.485 ± 0.195	0.515 ± 0.189	0.44	**1**
Dec 08	2.9 ± 4.5	2.5 ± 3.5	0.92	**1**	0.375 ± 0.196	0.531 ± 0.196	**<0.001**	**1**
Jan 09	3.9 ± 5.2	2.7 ± 3.5	0.41	**1**	0.482 ± 0.209	0.571 ± 0.190	**0.02**	**1**
Feb 09	3.0 ± 4.3	2.3 ± 3.4	0.37	**1**	0.364 ± 0.198	0.517 ± 0.187	**<0.001**	**1**
Mar 09	2.2 ± 4.0	3.0 ± 4.3	**0.04**	**1**	0.244 ± 0.178	0.418 ± 0.207	**<0.001**	**1**
Apr 09	2.2 ± 4.1	2.6 ± 3.5	**0.02**	**1**	0.175 ± 0.149	0.378 ± 0.160	**<0.001**	**1**
May 09	1.9 ± 3.3	1.7 ± 2.6	0.62	**1**	0.084 ± 0.092	0.239 ± 0.164	**<0.001**	**1**
Jun 09	1.5 ± 2.8	2.6 ± 4.1	**0.002**	**1**	0.107 ± 0.110	0.320 ± 0.129	**<0.001**	**1**
Jul 09	2.2 ± 3.4	1.9 ± 3.2	0.85	**1**	0.129 ± 0.130	0.313 ± 0.169	**<0.001**	**1**
Sep 09	3.6 ± 4.8	2.4 ± 3.6	0.20	**1**	0.110 ± 0.111	0.317 ± 0.133	**<0.001**	**1**
Nov 09	N/A ± N/A	4.4 ± 4.9	N/A	-	N/A ± N/A	0.936 ± 0.190	N/A	-
Jan 10	N/A ± N/A	4.4 ± 5.6	N/A	-	N/A ± N/A	0.889 ± 0.181	N/A	-
Mar 10	7.0 ± 6.4	2.5 ± 3.6	**0.003**	**1**	0.575 ± 0.222	0.719 ± 0.247	0.10	**1**
May 10	2.2 ± 3.9	0.9 ± 1.6	**0.03**	**1**	0.172 ± 0.167	0.308 ± 0.212	**<0.001**	**1**
Jul 10	1.2 ± 2.4	1.8 ± 2.7	**0.02**	**1**	0.152 ± 0.129	0.236 ± 0.178	**0.03**	**1**

4.2 Discussion

4.2.1 Temporal and spatial changes in fine sediment deposition and storage within seasonally-changing vegetated reaches

The null hypothesis stating that seasonal changes in macrophyte cover and their spatial arrangement do not influence seasonal patterns fine sediment retention and storage is rejected based on the results from this study.

Spatial patterns of deposited fine sediment were strongly associated with macrophyte patches at both study sites throughout the two year survey period. There were patches of fine sediment present within unvegetated sections of the reach, but these were considerably smaller and infrequent compared to those within vegetated patches. This was most likely because of the high velocity water flowing around patches, causing fine sediment around the perimeter of patches to be entrained. Fine sediment depth, water flow velocities and total water depths were found to be significantly different between open and vegetated areas in both reaches. Water flow velocities and total depths were significantly greater in open areas, and sediment depths were significantly higher in vegetated parts of the reach. The results indicate support for the findings of other workers (Chambers *et al*., 1991; Champion and Tanner, 2000; Green, 2005b; Sand-Jensen, 1998; Sand-Jensen and Mebus, 1996; Statzner *et al*., 2006; Wharton *et al*., 2006) who have described a transition in water flow velocities between open and vegetated areas in lowland river and stream cross-sections previously.

Additionally, high levels of fine sediment storage have been observed within vegetated areas in comparative studies on the Frome-Piddle catchment by Cotton *et al*. (2006), Heppell *et al*. (2009), Wharton *et al*. (2006) and Watson (2007). Other workers have previously highlighted the high capacity for fine particulate sediment retention within *Ranunculus*-dominated streams (Clarke and Wharton, 2001; Cotton *et al*., 2006; Heppell *et al*., 2008; Wharton *et al*., 2006). Chalk streams exhibit one of the best examples of clearly demarcated macrophyte patch mosaics that are separated by sediment-free gravel corridors (Sear *et al*., 1999; Walling and Amos, 1999).

The total weight of fine sediment in each survey month at the Bere Stream did not equal the combined weight of fine sediment from *Ranunculus* and *Nasturtium*.

Areas of surficial fine sediment deposited within unvegetated patches on the Bere Stream were rarely observed within this current study, contrary to there being considerable fine sediment deposition found in unvegetated areas by Heppell *et al*. (2009) and Welton (1980). Additionally, the total weight of fine sediment within *Ranunculus* patches did not equal the total weight of fine sediment stored within the reach at Frome Vauchurch on the River Frome. The difference in fine sediment storage at both sites was indicative of considerable fine sediment deposits stored within the marginal vegetation. This was comparable to the previous observations by Heppell *et al*. (2009) and Gurnell *et al*. (2006), who determined that high flow velocities created by in-stream macrophyte patches directed flow towards the stream margins, subsequently supplying fine sediments to the margins (Gurnell *et al*. 2006). The volume of sediment per m^2 of marginal vegetation cover was considerable on both study sites. Marginal vegetation at Frome Vauchurch had considerably greater volumes of fine sediment per unit area in comparison with marginal vegetation on the Bere Stream.

Overall, there appeared to be no seasonal pattern in the total weight of fine sediment stored at either site on the Bere Stream or River Frome within this current study, which also corresponds with the findings of the study by Heppell *et al*. (2009). However, when the weight of fine sediment within *Ranunculus* and *Nasturtium* patches on the Bere Stream was analysed, it did appear to correspond with seasonal changes in patch cover within the reach. Increased fine sediment storage within *Ranunculus* patches was observed on the Bere Stream when *Ranunculus* cover was at its peak between March 2009 and June 2009. The peak of fine sediment storage within *Nasturtium* patches coincided with the months that possessed the greatest area cover of *Nasturtium*, between July 2008 and January 2009. The weight of sediment stored within the channel at Frome Vauchurch was considerably greater in comparison with the Bere Stream which concurred with the findings of Heppell *et al*. (2009). Therefore the fifth null hypothesis that there are no differences in between the two lowland streams in relation to seasonal fine sediment storage and volume at the reach scale is rejected on this basis. This may suggest that the supply of fine sediment by suspension and by saltation is greater within the reach at Frome Vauchurch than that at the Bere Stream. The retention and storage of fine sediment within a river channel is normally dependant on the supply of fine sediment from the upstream (Gurnell *et al*., 2006). Another possibility is that the difference in retained fine sediment between the two sites is a reflection of the differences in retention capacity, which is in turn possibly influenced by changes in seasonal macrophyte cover and morphology at both sites.

Values of fine sediment weight on the Bere Stream at Snatford Bridge in this study were generally greater than those reported by Heppell *et al*. (2009). Also fine sediment storage values reported in their study on the Maiden Newton reach between May 2003 and October 2003 were considerably greater in comparison with those observed at Frome Vauchurch in this current study. The reach at Maiden Newton on the River Frome is located further upstream of the Frome Vauchurch reach in this current study. The Maiden Newton site is also upstream of the River Frome-River Hooke confluence. This difference in longitudinal positioning on the River Frome, as well as the time lapse between the two studies may have contributed to the differences in the fine sediment storage and delivery between the two reaches.

The reach at Snatford Bridge on the Bere Stream used by Heppell *et al*. (2009) was the same as that used by this current study, but they used a longer reach (40 m) in comparison to this study (30 m). Differences in sediment storage values may have been due to the time difference between observations of this current study and their study, as well as differences in macrophyte community assemblage and fine sediment supply. Furthermore, values of discharge measured during this current study on the Bere Stream were a magnitude greater than those measured during the observation period in the study by Heppell *et al*. (2009).

4.2.2 Seasonal changes of the fine sediment characteristics within lowland vegetated reaches

The results of this study suggest that the physical characteristics of fine particulate sediment do not vary on a seasonal basis within *Ranunculus* patches at the reach scale. Therefore the second null hypothesis is accepted on this basis.

Analyses of fine sediment characteristics within *Ranunculus* patches determined that mean particle D_{50} values from the Bere Stream and Frome Vauchurch were within the medium sand and fine to coarse sand correspondingly. This suggests that the majority of retained fine sediment within mid-channel *Ranunculus* patches originated from fine sediment saltating as bed material (Cotton *et al*., 2006; Phillips and Walling, 1999).

Effective sediment samples from both sites and absolute sediment samples from the Bere Stream were found to contain particle D_{50} values between fine and coarse sand (125 to 1000 μm). Absolute median particles sizes from Frome Vauchurch were between medium silt and coarse sand (16 to 1000 μm). This was different to the previous analyses on fine sediment from mid-channel vegetation by Heppell *et al.* (2009). Their study determined that median particle sizes were of medium and fine sand grade on the Bere Stream at Snatford Bridge and River Frome at Maiden Newton respectively. The differences in particle D_{50} values on the Bere Stream between this study and that of Heppell *et al.* (2009) may be due to the inclusion of fine sediment samples taken from mid-channel *Nasturtium* patches in their study.

Watson (2007) showed that both the size and morphology of macrophytes does have an impact on the particle retention in relation to the particle size, as well as their position within stream.

Values of particle D_{50} within the effective and absolute sediments from both sites in this current study were observed to be generally decreasing over the two year period, starting with a greater range in sandy sediment in July 2008 and ending with considerably finer sand in July 2010. This did not correspond with the study by Cotton *et al.* (2006) who reported that absolute fine sediments were composed of majority fine sand grade sediment throughout their measurement period at Maiden Newton. The particle D_{50} within effective and absolute fine sediment samples were determined to be significantly different to one another within the Bere Stream, but this was not the case at Frome Vauchurch. This infers that both sediment fractions at Frome Vauchurch comprise of organic and inorganic sediment particles which possess similar particle D_{50} values. The particle D_{50} values within the effective and absolute fractions were found to be highly variable between some sample months at both field sites, but this was not reflected in any seasonally changing patterns.

The volume of silt and clay sized particles within effective sediment samples on the Bere Stream were not found to have a clear seasonal pattern, this was also the case at the Frome Vauchurch site. Additionally there was no seasonal variation in the volume of silt and clay particles within the absolute sediment fractions of sediment samples taken from Frome Vauchurch. Significant differences were found between effective and absolute volumes of silt and clay sized particles within sediment samples from Frome Vauchurch. Also, large differences between the effective and absolute volumes of silt and clay sized particles were found within the Bere Stream, with the absolute fraction containing noticeably higher volumes of silt and clay sized particles. Silt and clay particles deposited on the Bere Stream at Snatford Bridge have already been identified as being mostly from an agricultural origin (Collins and Walling, 2007a; Heppell *et al*., 2009).

The % organic matter content within sediment samples from the Bere Stream and Frome Vauchurch appeared largely comparable. However, the Bere Stream had a greater number of outlier values, and also the highest % organic matter content within a single sample at 50 %. There were no seasonal patterns in the % organic matter within sediment samples at either site. Although fine sediment samples from Frome Vauchurch appeared to have a more noticeable variations in comparison with those from the Bere Stream. Higher mean values of % organic matter in July 2008, July 2009, September 2009 and July 2010 in comparison with other months. This was also different to the observations made by Heppell *et al*. (2009) on their study of the Maiden Newton site on the River Frome. Temporal and compositional changes in the supply of fine sediment are the most likely reason for differences in organic matter content in the fine sediment between this study and the study by Heppell *et al*. (2009). Additionally, the mixing of fine sediment supplied by the River Hooke and River Frome could have been a dominant factor.

The organic matter content within sediment samples taken from mid-channel vegetation on the Bere Stream presented by Heppell *et al*. (2009) was comparable to those found within sediment samples in this current study, with the exclusion of large increases in organic matter in their study between September 2003 and January 2004. Heppell *et al*. (2009) explained that this was due to the encroachment of *Nasturtium* patches into the channel during the autumn-winter period of their study. Encroachment of *Nasturtium* patches into the centre of the channel was also observed in this present study during the autumn periods in 2008 and 2009, but no sediment samples were retrieved from these patches. It is probable that there was little difference in fine sediment characteristics between *Nasturtium* and *Ranunculus* patches in the centre of the channel, due to the colonisation of *Nasturtium* on top of *Ranunculus* patches that were present previously.

4.2.3 Differences in fine sediment deposition between patches of *Nasturtium* and *Ranunculus*

The results of this study suggest that the retention of fine sediment does differ between different macrophyte species at the reach scale, and therefore the third null hypothesis can is rejected.

Statistical analyses of the survey results established that patches of *Nasturtium* had significantly greater depths of fine sediment in comparison with *Ranunculus* patches. With the exception of some summer months (July 2008, June 2009, July 2009 and July 2010) and some winter months (November 2008, December 2008 and January 2010).

Considerably high seasonal macrophyte cover combined with seasonally lower suspended sediment concentrations, in addition to lower channel discharge in the summer months of July 2008, 2009 and 2010 possibly created a situation where the interception of fine sediment was equal throughout the reach. A further reason may be that *Nasturtium* was beginning to grow over the top of established *Ranunculus* patches within the middle of the channel because of the stable conditions created by high *Ranunculus* cover and lower seasonal flow velocities (Biggs, 1996). This would mean that the depth of fine sediment within mid-channel *Nasturtium* patches were equivalent to those of *Ranunculus* patches.

Within the months of November 2008, December 2008 and January 2010 the depths of fine sediment within *Nasturtium* and *Ranunculus* patches were determined to be similar. This was probably because patches of both species provided adequate protection for deposited fine sediment against increased seasonal discharge and mean flow velocity within the channel. Similar observations were also made by previous studies on chalk streams (Gurnell *et al*., 2006; Heppell *et al*., 2009). This may suggest the presence of an upper storage threshold for fine sediment within macrophyte patches during winter periods that is independent of species type. It is possible that this may be dependant on seasonal flow conditions and fine sediment supply within either channel.

4.2.4 Differences in fine sediment deposition between emergent and submergent *Ranunculus* patches

The results of this study found there were significant differences in fine sediment depth and water velocities were found between emergent and submergent *Ranunculus* patches at both sites. Therefore the fourth null hypothesis is rejected and the alterative hypothesis accepted on this basis. Sediment depths within emergent patches were greater than those within submergent patches on the Bere Stream, with the opposite relationship found on the River Frome.

There are a few possible explanations for why a difference in the observations occurred between the two study sites. Firstly the longevity of the *Ranunculus* patches at both sites were observed to differ greatly, with *Ranunculus* patches at Frome Vauchurch persisting over winter periods more successfully compared to those at the Bere Stream. Secondly, the erratic changes in stage and discharge on the Frome Vauchurch site may have contributed to a greater number of emergent patches being misidentified as submergent due to greater stage values during reach surveys. Lastly, differences in fine sediment supply and subsequent interception by patches at each site may have contributed to higher sediment depths in submergent patches on the Frome Vauchurch site. The fraction of fine sediment being transported by saltation at Frome Vauchurch may have been greater in comparison to the Bere Stream. If this was the case, it may be that submergent patches on the Frome Vauchurch site were able to intercept and accumulate greater depths of fine sediment due to a comparatively greater supply of fine sediment as bedload.

CHAPTER 5

The impact of seasonally-changing macrophyte cover on fine sediment transport at the reach scale

5.0 Introduction

This chapter reports on the results (section 5.1) and discussion (section 5.2) relating to seasonal experimental corn pollen releases conducted between July 2008 and July 2010 on the Bere Stream at Snatford Bridge and Frome Vauchurch on the River Frome. Seasonal changes in macrophyte cover and channel porosity are compared with corresponding parameters of fine sediment transport and deposition at both sites.

5.1 Results

5.1.1 Seasonal corn pollen releases on the Bere Stream

Table 5.1 provides a summary of the results from the experiments on the Bere Stream. The seasonal variations in values of F_X, S_P, K_P and V_{dep} are described in detail in the following sections.

5.1.1.1 Seasonal changes in transport efficiency (F_X)

Figure 5.1 shows the changes in macrophyte seasonal cover, discharge and corn pollen transport efficiency (F_X) from experimental releases on the Bere Stream between July 2008 and July 2010.

Values of F_X were observed to correspond with the total macrophyte cover within the reach from July 2008 to November 2008 (Figure 5.1). There was an increase in F_X between July and September 2008 from 49 to 64 % respectively. This was followed by a slight decrease from September to November 2008 (61 %) and a subsequently slightly higher F_X value of 62 % in January 2009. The total macrophyte cover during the same period had decreased from 70 % in July 2008 to 43 % in January

Table 5.1– The parameters and results from each corn pollen release on the Bere Stream at Snatford Bridge from July 2008 to July 2010. $\mathbf{F_X}$ –transport efficiency of corn pollen , **Q** – discharge, $\mathbf{S_P}$ – mean transport distance of released particles, $\mathbf{K_P}$ – longitudinal loss rate of released particles, $\mathbf{V_{dep}}$ – depositional velocity of released particles, **u** – mean velocity, **h** – mean channel depth, **T** - the mean time in suspension of released particles. Please refer to section 3.7 for further details for each of these parameters

Month	No. CP in transport	F_X	Total macrophyte cover (%)	Q (m^3 s^{-1})	S_P (m)	K_P (m^{-1})	V_{dep} (mm s^{-1})	u (m s^{-1})	h (m)	T (s)
Jul-08	1274516	49	70	0.39	42.1	0.024	2.10	0.34	0.26	123
Sep-08	1667073	64	75	0.48	67.5	0.015	2.36	0.54	0.30	126
Nov-08	1581733	61	61	0.49	60.4	0.017	3.54	0.74	0.29	81
Jan-09	1605153	62	43	0.58	62.2	0.016	2.91	0.60	0.30	104
Mar-09	2089671	80	44	0.59	137.3	0.007	0.82	0.36	0.32	385
May-09	0698211	27	81	0.33	22.8	0.044	3.38	0.28	0.28	83
Jul-09	0919631	35	81	0.44	28.9	0.035	3.87	0.46	0.24	63
Sep-09	2247784	86	49	0.50	206.1	0.005	0.53	0.65	0.17	318
Nov-09	2501269	96	57	1.04	774.9	0.001	0.23	0.68	0.26	1137
Jan-10	2401461	92	33	1.56	377.7	0.003	0.56	0.66	0.32	570
Mar-10	1343863	52	45	0.79	45.5	0.022	4.24	0.65	0.30	70
May-10	2359178	91	74	0.53	308.6	0.003	0.34	0.38	0.28	823
Jul-10	1704353	66	71	0.32	71.0	0.014	1.23	0.33	0.26	214

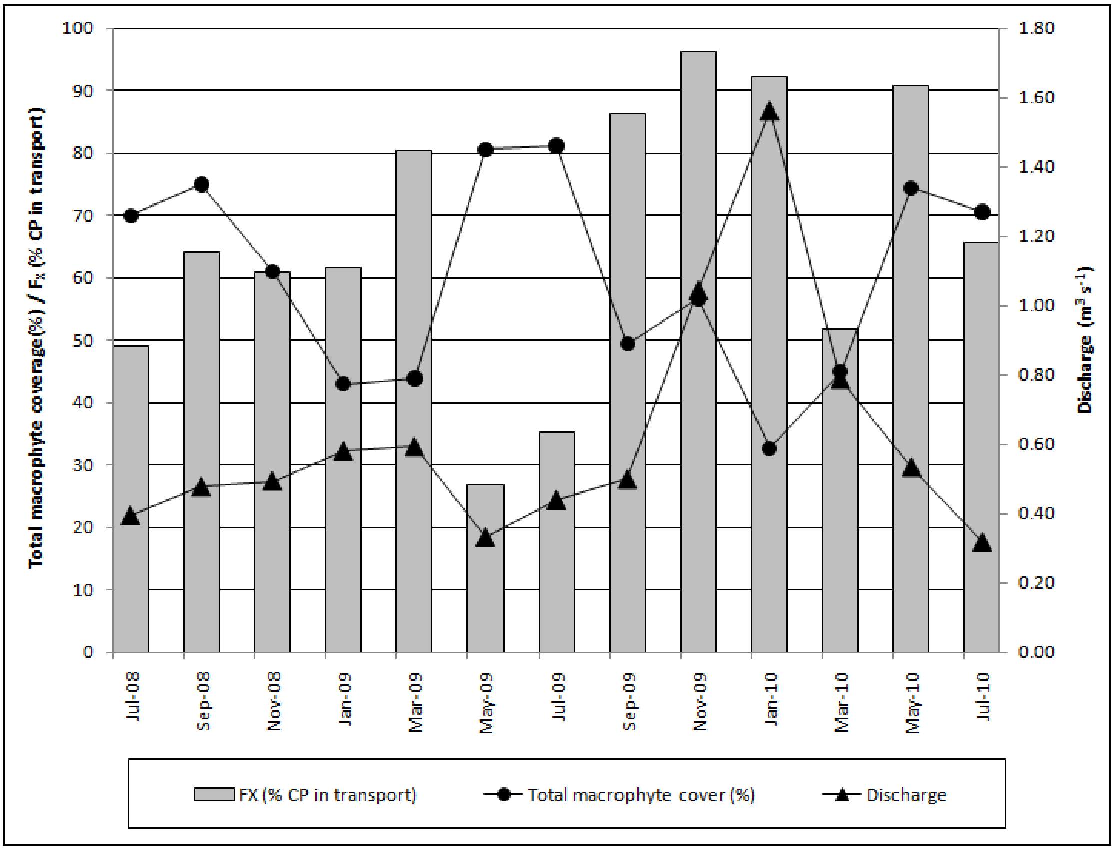


Figure 5.1 – The transport efficiency (F_X) within seasonal releases with corresponding changes in total macrophyte cover (%) and discharge (m^3 s^{-1}) between July 2008 and July 2010 on the Bere Stream at Snatford Bridge.

2010. The change in F_X also coincided with notable a increase in discharge values during releases from July 2008 to January 2009.

In March 2009 F_X had increased to 80 % which was the peak value within the entire dataset. It was not clear why such a change in F_X occurred in March 2009. However it corresponded with a change in *Ranunculus* and *Nasturtium* cover and distribution (see section 4.1.1). *Ranunculus* became the dominant macrophyte within the channel and *Nasturtium* had receded to a minimum cover (7 %) in the margins. Further coincidental changes occurred including a lower mean channel water velocity (0.36 m s^{-1}) and a greater mean depth (0.32 m) within the reach. It may be possible that one or a combination of all of these factors contributed to promoting conditions higher levels of corn pollen particle transport.

Following March 2009 F_X had dramatically decreased to 27 % in May 2009 and 35 % in July 2009. The change in F_X corresponded with a decrease in discharge to 0.33 and 0.44 m^3 s^{-1} in May 2009 and July 2009 respectively, as well as a high area cover of macrophytes (81 %) within the reach. The increase in total vegetation cover was composed of increasing *Nasturtium* and *Apium* cover (See section 4.1.1).

Between July 2009 and January 2010 the value of F_X had increased sharply with peaks in transport of 96 and 92 % occurring in November 2009 and January 2010 correspondingly. The peak in F_X during November 2009 occurred in parallel with an increase in mean channel flow velocity (0.68 m s^{-1}). Discharge during this period increased notably to 1.56 m^3 s^{-1} in January 2010. A similar increase in total macrophyte cover occurred in November 2009 to 57 %, followed by a notable decrease to 33 % in January 2010. The changes in total macrophyte area cover were due to a loss of *Nasturtium* and *Apium* cover combined with an increase in *Ranunculus* cover.

From January 2010 there was an initial decrease in F_X to 52 % in March 2010 succeeded by a prominent increase of 91 % in May 2010, and a subsequent decrease to 66 % in July 2010. The decrease and increase in F_X during March 2010 and May 2010 correspondingly, coincided with a decrease and subsequent increase in total macrophyte cover from 45 to 74 % respectively. There was also a steady decrease in discharge, mean flow velocity and mean channel depth during the same period.

5.1.1.2 Seasonal changes in longitudinal loss rate (K_P)

The longitudinal loss rate (hereafter as K_P) represents the rate of loss over the distance (m) of the reach (Figure 5.2) rather than the actual number of particles in transport.

Changing seasonal values of K_P from the experimental releases on the Bere Stream are described with corresponding changes of total macrophyte cover (%) in Figure 5.3. K_P decreased from 0.024 m^{-1} in July 2008 to 0.015 and 0.017 m^{-1} in September 2008 and November 2008 respectively. This was followed by a slight decrease in K_P in January 2009 (0.016 m^{-1}) followed by a decrease in March 2009 to 0.007 m^{-1}. The decrease in March 2009 was succeeded by an increase in K_P in May 2009 of 0.044 m^{-1}. This was the highest rate of loss for corn pollen within the two year dataset. K_P then increased to 0.035 m^{-1} in July 2009, representing a greater rate of loss in comparison to that of July 2008 with a 0.010 m^{-1} difference between the two. The two highest values of K_P also coincided with the highest cover of macrophytes within the reach. There was a conspicuous decrease in K_P to 0.001 m^{-1} within the November 2009 release, which was accompanied by an increase in mean channel flow velocity and mean water depth. The next large increase in K_P occurred in March 2010 (0.022 m^{-1}), which corresponded with a sizable decrease in discharge and an increase in *Ranunculus* cover within the reach. Following March 2010 K_P decreased to 0.003 m^{-1} and subsequently after increased to 0.014 m^{-1} in May 2010 and July 2010.

5.1.1.3 Seasonal changes in mean transport distance (S_P)

The mean transport distance (m) (hereafter referred to as S_P) is the mean distance travelled by a corn pollen particle from the release site. S_P values are intrinsically linked to values of K_P because they are the direct inverse of K_P (See section 3.7.4) as illustrated in Figure 5.4. An increase in particle K_P will translate to a direct decrease in the values of S_P for released particles.

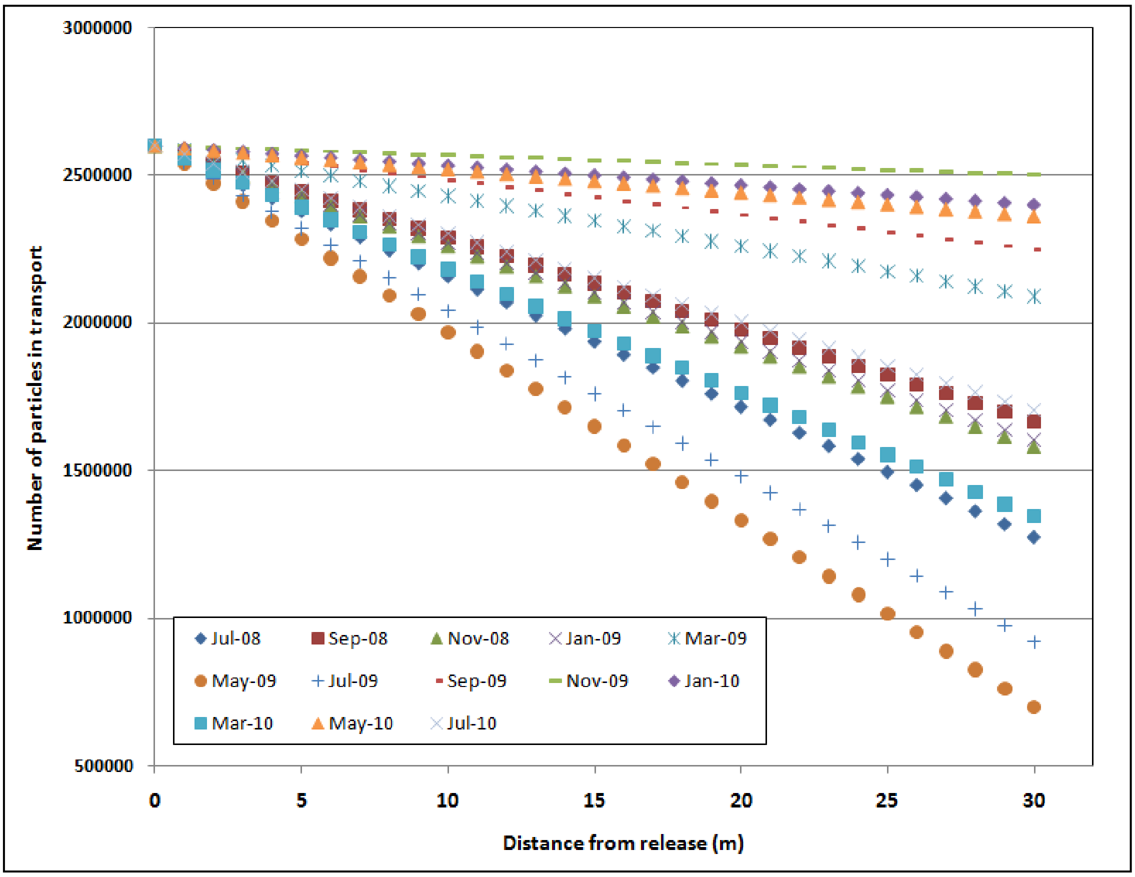


Figure 5.2 – The loss of particles from transport per metre of the stream length during particle analogue releases with corn pollen within the Bere Stream at Snatford Bridge between July 2008 and July 2010. Each line illustrates the loss of corn pollen particles determined from the resulting values of K_P.

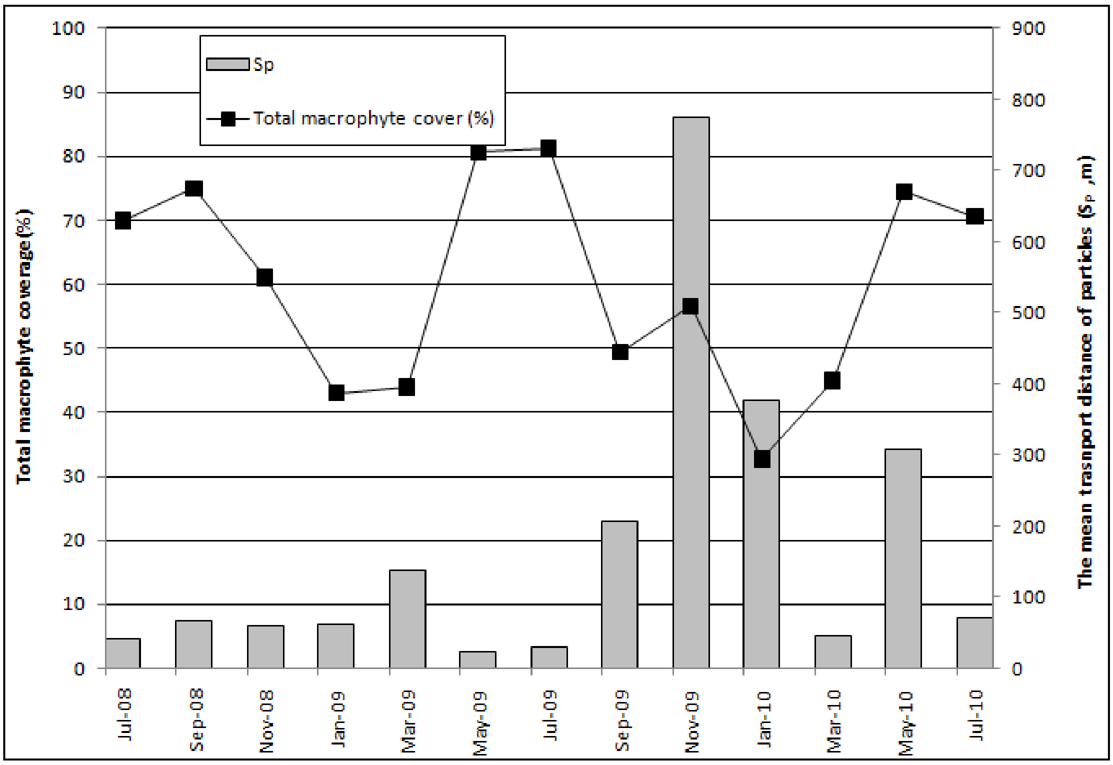


Figure 5.3 – Changes in the mean transport distance (S_P, m) of corn pollen from the seasonal releases and corresponding changes in total macrophyte cover on the Bere Stream at Snatford Bridge between July 2008 and July 2010.

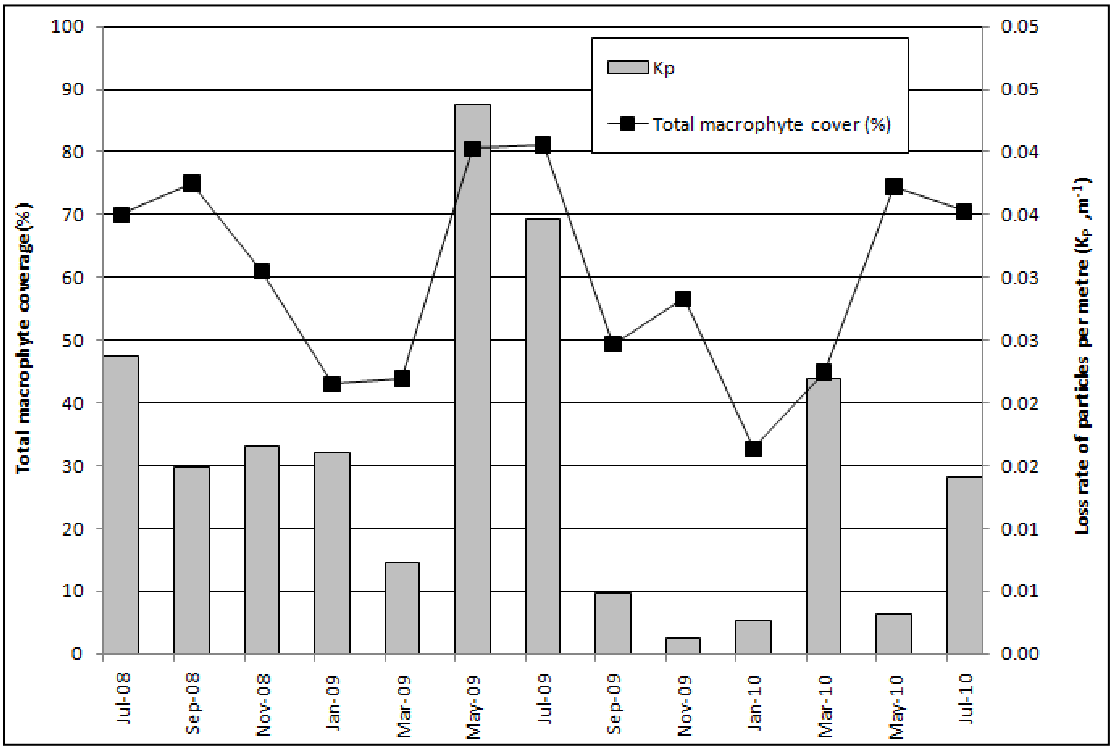


Figure 5.4 – Changes in the longitudinal loss rate (K_P, m^{-1}) of corn pollen from the seasonal releases and corresponding changes in total macrophyte cover on the Bere Stream at Snatford Bridge between July 2008 and July 2010.

Within the July 2008 release S_P was 42 m, following this values of S_P then increased to 68 and 60 m in September 2008 and November 2008 respectively, coinciding with conspicuously low K_P values within the reach (see section 5.1.1.2). In January 2009 corn pollen particles failed to be transported out of the reach (27 m), and this coincided with an increase in K_P (0.038 m^{-1}). In March 2009 S_P had a noticeably greater value (137 m), this indicated that the distance travelled by the corn pollen was over four times the length of the release reach. S_P was then considerably lower in May and July 2009 at 23 and 29 m correspondingly. May 2009 had the lowest S_P in the entire dataset which coincided with a high value for K_P (0.044 m^{-1}).

Values of S_P were greatest in the releases between September 2009 and January 2010, which corresponded with the greatest F_X values and lowest K_P values. The greatest value for S_P was 775 m which is approximately 26 times the length of the experimental reach.

S_P then successively decreased to 378 and 45 m in January 2010 and March 2010 correspondingly. A further increase to 309 m followed in May 2010 before notably decreasing to 71 m in July 2010.

5.1.1.4 Seasonal changes of the mean time that particles were suspended (T)

The mean time of particles in suspension (hereafter referred to as T) is the mean time in seconds (s) that released corn pollen particles spend in suspension before deposition (See Section 3.7.5). It is mathematically related to the S_P parameter, and incorporates the mean water velocity (U_W, m s^{-1}) measured within the reach at the time of the release.

Corn pollen particles released in July and September 2008 were suspended in the water column for 123 and 126 s correspondingly (Figure 5.5). This was followed by a decrease to 81 s and a subsequent increase to 104 s in November 2008 and January 2009 respectively. The value of T in March 2009 then markedly increased to 384 s, before decreasing to 83 and 63 s in May and July 2009 respectively. The value of T in July 2009 was the lowest within the dataset, indicating that on average released corn pollen particles spent just over one minute in suspension before being deposited.

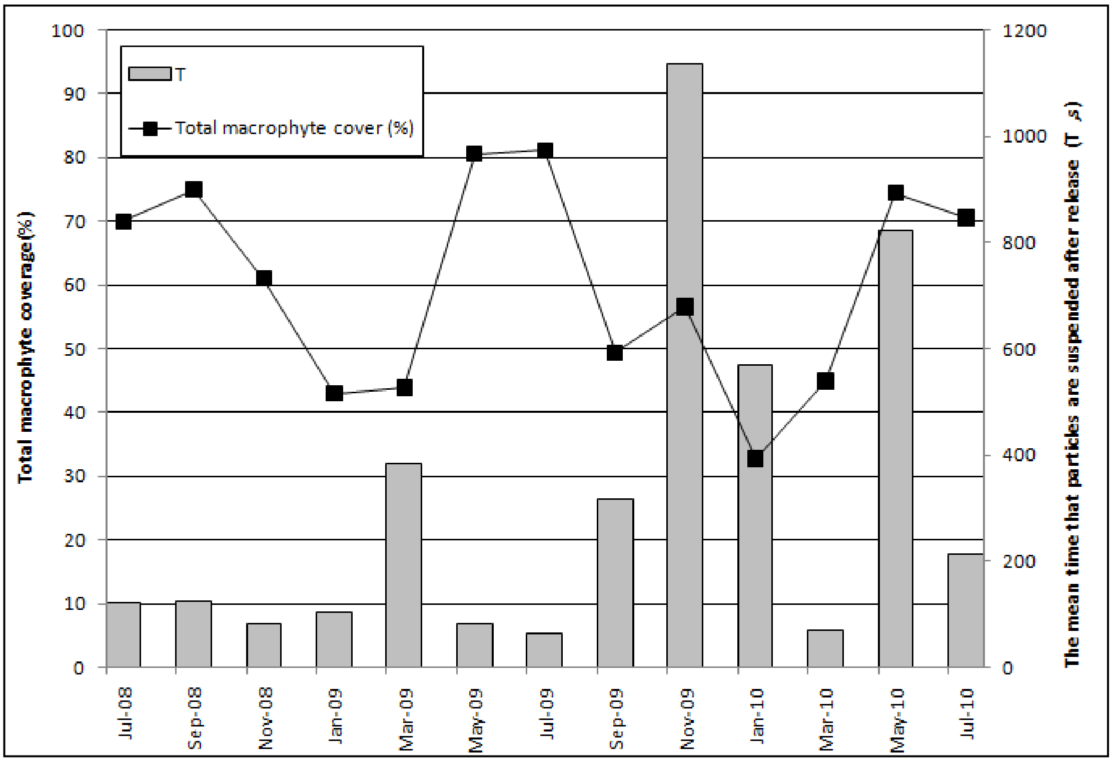


Figure 5.5 – Changes of the mean time that corn pollen remained suspended (T, s) within each seasonal release and corresponding changes in total macrophyte cover on the Bere Stream at Snatford Bridge between July 2008 and July 2010.

The greatest values of T occurred within releases between September 2009 and January 2010. This corresponded with the greatest values of F_X and S_P, and lowest values for K_P. The peak value for T was seen in the November 2009 release at 1137 s. Following this T decreased notably in March 2010 to 70 s, before increasing further to 823 s in May 2010 and decreasing to 214 s in July 2010.

5.1.1.5 Seasonal changes in deposition velocity (V_{dep})

The depositional velocity (hereafter as V_{dep}) is the rate at which particles leave the water column. The given value indicates a rate of deposition that removes the influence of depth and flow velocity due to the nature in which it is calculated (See section 3.7.6).

Overall, V_{dep} appeared not to correspond with seasonal changes in total macrophyte cover between July 2008 and July 2010 on the Bere Stream (Figure 5.6). V_{dep} increased from 2.10 mm s^{-1} in July 2008 to 2.36 mm s^{-1} in September 2008, this was then followed by a conspicuous increase in November 2008 (3.54 mm s^{-1}) and a decrease to 2.91 mm s^{-1} in January 2009. There was a notable decrease in V_{dep} in March 2009 to 0.83 mm s^{-1}. V_{dep} increased to 3.38 mm s^{-1} and 3.87 mm s^{-1} in May and July

2009 correspondingly. Some of the lowest values of V_{dep} were determined within September 2009, November 2009 and January 2010 release months. March 2010 had the greatest value of V_{dep} within the two year dataset at 4.24 mm s^{-1}, and November 2009 had the lowest value of 0.23 mm s^{-1}. V_{dep} in July 2010 was significantly lower than the previous July releases within the two year dataset at 1.22 mm s^{-1}.

5.1.1.6 Statistical analyses of release parameters in Bere Stream releases

A Pearson Product-Moment correlation analysis (Table 5.2) was used to explore linear correaltions between the ecological, geomorphological and hydrological variables measured within the channel during each release. The strength within a linear correlation was assessed with coefficient ***r*** values and their corresponding *P*-values. The significance of the *P*-values where assessed at the alpha level of 0.05 with 11 degrees of freedom, with *P*-values of <0.05 being statistically significant.

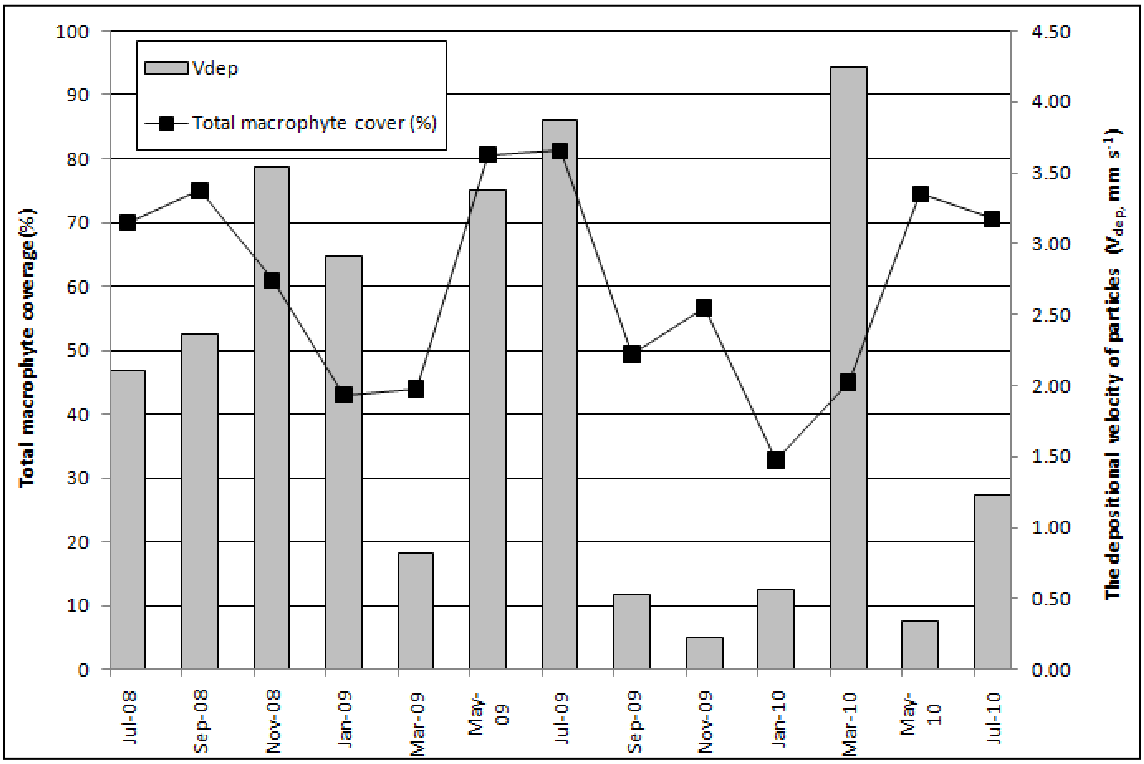


Figure 5.6 – The values of particle deposition velocity (V_{dep}, mm s^{-1}) within each seasonal release and corresponding changes in total macrophyte cover on the Bere Stream at Snatford Bridge between July 2008 and July 2010.

Table 5.2 – The results matrix from a Pearson Product-Moment correlation analysis of the release parameters from analogue particle releases on the Bere Stream at Snatford Bridge. To indicate the strength of each correlation there is a correlation coefficient value or *r* value and an associated statistical significance (*P* value) with 11 degrees of freedom (*d.f.*). The significant of the correlation is assessed at an alpha level of 0.05. High *r* correlation values and significant *P*-values are highlighted. F_X –particle transport efficiency, TV % cover - total vegetation % cover, R % cover – *Ranunculus* % cover, N % cover – *Nasturtium* % cover, MV % cover – marginal vegetation % cover, Q – discharge, u – mean channel velocity, h – mean channel depth (from the waters' surface), NTT – nominal transport time, CW – mean channel width, W: D – Width to depth ratio, K_P – longitudinal loss rate, S_P – mean particle transport distance, V_{dep} – depositional velocity, T – average time in suspension, Manning's –Manning's N number of the channel, Re - Reynolds number of the channel, and Shear stress – Channel shear stress (N/m^2). AC in the results matrix indicates that result values were not added because of autocorrelation.

		F_X	TV % cover	R % cover	N % cover	MV % cover	Q	u	h	NTT	CW	W:D	Sp	Kp	Vdep	T
TV % cover	*r*	-0.532														
	P	0.061														
R % cover	*r*	-0.229	0.328													
	P	0.452	0.274													
N % cover	*r*	-0.113	0.266	**-0.643**												
	P	0.712	0.380	**0.018**												
MV % cover	*r*	-0.303	**0.615**	0.041	-0.149											
	P	0.314	**0.025**	0.894	0.628											
Q	*r*	**0.573**	**-0.689**	-0.222	-0.237	-0.353										
	P	**0.041**	**0.009**	0.465	0.435	0.236										
u	*r*	0.383	**-0.576**	**-0.687**	0.381	-0.436	**0.555**									
	P	0.197	**0.040**	**0.009**	0.199	0.137	**0.049**									
h	*r*	-0.012	-0.262	0.311	-0.074	**-0.650**	0.355	-0.044								
	P	0.969	0.388	0.300	0.810	**0.016**	0.234	0.886								
NTT	*r*	-0.463	**0.611**	**0.691**	-0.394	0.498	**-0.561**	**-0.983**	0.017							
	P	0.111	**0.027**	**0.009**	0.183	0.083	**0.046**	**0.000**	0.956							
CW	*r*	-0.120	-0.350	0.349	-0.447	-0.322	0.369	-0.135	**0.706**	0.116						
	P	0.697	0.241	0.242	0.126	0.284	0.215	0.660	**0.007**	0.706						
W:D	*r*	0.082	0.078	-0.327	-0.024	0.547	-0.252	0.095	**-0.976**	-0.079	**-0.626**					
	P	0.790	0.799	0.275	0.939	0.053	0.406	0.757	**0.000**	0.797	**0.022**					
K_P	*r*	AC	**0.562**	0.295	0.036	0.363	-0.522	-0.420	-0.016	0.515	0.093	-0.057	AC			
	P		**0.045**	0.328	0.908	0.222	0.067	0.153	0.958	0.072	0.764	0.854				
V_{dep}	*r*	AC	0.261	0.047	0.266	-0.047	-0.362	0.053	0.159	0.020	0.178	-0.206	AC	AC		
	P		0.390	0.878	0.379	0.879	0.224	0.864	0.605	0.948	0.560	0.500				
T	*r*	AC	-0.189	0.026	-0.238	0.013	0.543	0.160	-0.013	-0.191	-0.008	0.009	AC	AC	AC	
	P		0.535	0.932	0.434	0.965	0.055	0.602	0.968	0.531	0.978	0.976				
S_P	*r*	AC	-0.284	-0.217	-0.113	0.026	**0.653**	0.365	-0.061	-0.373	-0.042	0.062	AC	AC	AC	AC
	P		0.346	0.476	0.713	0.933	**0.015**	0.220	0.844	0.209	0.892	0.842				
Mannings	*r*	**-0.666**	**0.826**	0.343	-0.029	**0.750**	-0.541	**-0.627**	-0.302	**0.709**	-0.285	0.169	-0.318	**0.749**	0.311	-0.288
	P	**0.013**	**0.001**	0.252	0.925	**0.003**	0.056	**0.022**	0.316	**0.007**	0.346	0.582	0.290	**0.003**	0.301	0.340
Re	*P*	0.376	**-0.842**	-0.103	-0.138	**-0.849**	**0.618**	0.488	**0.676**	-0.529	**0.593**	-0.539	0.155	-0.430	-0.023	0.122
	r	0.205	**0.000**	0.737	0.654	**0.000**	**0.025**	0.091	**0.011**	0.063	**0.033**	0.057	0.613	0.143	0.941	0.693
Shear stress	*r*	-0.182	0.004	0.329	0.010	-0.418	0.138	-0.170	**0.848**	0.185	0.542	**-0.881**	-0.063	0.191	0.268	-0.008
	P	0.551	0.989	0.272	0.974	0.156	0.653	0.580	**0.000**	0.546	0.056	**0.000**	0.838	0.533	0.377	0.980

A significant correlation was determined between F_X and discharge (***r*** 0.57, ***P*** = 0.04). No significant correlation were found between F_X and total vegetation cover (***r*** -0.53, ***P*** = 0.06), or between F_X and marginal vegetation (***r*** -0.30, ***P*** = 0.31) or between F_X and *Ranunculus* (***r*** -0.23, ***P*** = 0.45). A significant negative correlation was found between values of F_X and Manning's N numbers (***r*** -0.67, ***P*** = 0.01), which suggests that a decrease in the transport of corn pollen is related with increases in channel roughness. Values of Manning's N were also highly significantly correlated to variations in total vegetation cover (***r*** 0.83, ***P*** < 0.01) and marginal vegetation cover (***r*** 0.75, ***P*** <0.01), suggesting that channel roughness increased when total vegetation cover and in particular marginal vegetation cover increased.

There was a significant correlation between K_P and the total vegetation cover (***r*** 0.56, ***P*** = 0.04), as well as a highly significant correlation with Manning's N values (***r*** 0.75, ***P*** <0.01). This indicates that values K_P increase with increasing channel roughness. K_P values were not significantly correlated with marginal vegetation cover comprising a majority of *Apium* (***r*** 0.36, ***P*** = 0.22) or *Ranunculus* (***r*** 0.30, ***P*** = 0.33).

V_{dep} had no significant correlations with any of the other parameters. Values of S_P were only significant correlated with channel discharge (Q) (***r*** 0.65, ***P*** = 0.02). T was not significantly correlated with any of the measured or estimated parameters.

5.1.1.7 Summary of reach-scale experimental releases on the Bere Stream

The results suggest that increases in K_P values and decreases in F_X values for the released corn pollen particles were associated with seasonal increases in channel roughness that is represented by Manning's N values. These in turn appear to be correlated with changes in total macrophyte cover, and in particular marginal vegetation. Furthermore, increases in values of F_X were significantly correlated with increases in values of F_X. Seasonal variations in S_P and T were not associated with corresponding changes in the total cover of macrophytes or the cover of individual macrophyte species. But the results suggest that increases in discharge were related to increases in values of S_P. May 2009 and July 2009 had the lowest F_X, S_P and T values as well as the highest K_P and V_{dep} values. This coincided with the greatest values of macrophyte cover (81 %) in addition to seasonally low discharge values, and high values of Manning's N. Seasonal changes in F_X, S_P, T, K_P and V_{dep} were not correlated with corresponding changes in cover of *Ranunculus*, *Nasturtium* or the *Apium*-dominated marginal vegetation.

5.1.2 Seasonal corn pollen releases at Frome Vauchurch

Table 5.3 provides a summary of the results from the experiments on the River Frome at Frome Vauchurch. The seasonal variations in values of F_X, S_P, K_P, V_{dep} and T are described in detail in the following sections.

5.1.2.1 Seasonal changes in transport efficiency (F_X)

Seasonal fluctuations in F_X values generally corresponded with changes in total macrophyte cover with the exception of May 2009, July 2009, January 2010 and March 2010 (Figure 5.7). From September 2008 to November 2009 there was a decrease in F_X from 76 to 49 % respectively. This was followed by a further decrease in January 2009 to 38 %. F_X increased to 94 % in March 2009, which was the highest value in the entire dataset. Channel discharge was lower during the March 2009 experimental release than in the previous release in January 2009 (1.35 m^3 s^{-1}). Macrophyte cover had increased by 11 % in January 2009, and was primarily composed of *Ranunculus*. However the mean flow velocity and mean water depth in the channel had not changed significantly from January 2009 to March 2009. F_X values had decreased dramatically to 3 % in May 2009 and 1 % in July 2009. These were the lowest values for F_X in the whole of the Frome Vauchurch dataset. This coincided with an increase in macrophyte cover to the highest levels of cover at 72 and 62 % in May 2009 and July 2009 correspondingly, coupled with a general decrease in discharge in May 2009 and July 2009 to 0.54 and 0.68 m^3 s^{-1} respectively, in addition to lower mean flow velocities in May 2009 (0.16 m s^{-1}).

Table 5.3 – The parameters and results from each corn pollen release at Frome Vauchurch on the River Frome from September 2008 to July 2010. F_X –transport efficiency of corn pollen , Q – discharge, S_P – mean transport distance of released particles, K_P – longitudinal loss rate of released particles, V_{dep} – depositional velocity of released particles, u – mean velocity, h – mean channel depth, T - the mean time in suspension of released particles. Please refer to section 3.7 for further details for each of these parameters.

Month	No. CP in transport	F_X	Total macrophyte cover (%)	Q ($m^3 s^{-1}$)	S_P (m)	K_P (m^{-1})	V_{dep} (mm s^{-1})	u (m s^{-1})	h (m)	T (s)
Sep-08	1981846	76	61	0.66	110.5	0.009	0.68	0.20	0.37	540
Nov-08	1275523	49	45	1.81	42.1	0.024	5.00	0.46	0.46	92
Jan-09	0982130	38	37	2.05	30.8	0.032	5.31	0.35	0.47	88
Mar-09	2456976	94	48	1.35	530.2	0.002	0.29	0.33	0.48	1630
May-09	0044684	3	72	0.54	8.7	0.116	7.80	0.16	0.42	54
Jul-09	0031990	1	62	0.68	6.8	0.147	32.33	0.46	0.48	15
Sep-09	1913888	74	47	0.84	97.9	0.010	0.54	0.18	0.29	534
Nov-09	0942128	36	34	2.78	29.6	0.034	10.14	0.76	0.39	39
Jan-10	2103446	81	15	2.64	141.6	0.007	1.56	0.60	0.36	234
Mar-10	1959733	75	27	2.04	106.1	0.009	2.84	0.86	0.35	123
May-10	1037272	40	50	1.01	32.6	0.031	2.49	0.27	0.31	123
Jul-10	1895119	73	66	0.69	94.9	0.011	0.58	0.17	0.31	543

An increase in F_X occurred in September 2009 to 74 %, which coincided with a small increase in discharge (0.84 $m^3 s^{-1}$), a gradual decline in total macrophyte cover to 47 % as well as significant decreases in mean velocity and mean total depth. F_X fell significantly again in November 2009 to 36 %, which coincided with a further decrease in total macrophyte cover to 34 %, and high channel discharge at 2.78 $m^3 s^{-1}$. This was the highest discharge value during the seasonal releases. In January 2010 F_X increased considerably to 81 %, which corresponded with a further decrease in total macrophyte cover to 15 %, a high value of discharge (2.64 $m^3 s^{-1}$) and increased mean channel flow velocity of 0.6 m s^{-1}.

F_X decreased from 81 % in January 2010 to 40 % in May 2010. There were particularly high values of F_X in January 2010 and March 2010 (75 %). These coincided with high values of discharge from 2.64 in January 2010 to 2.04 $m^3 s^{-1}$ in March 2010, in addition to low total macrophyte cover at 15 and 27 % correspondingly in addition to increased mean flow velocities. Within the months of May 2010 and July 2010 changes

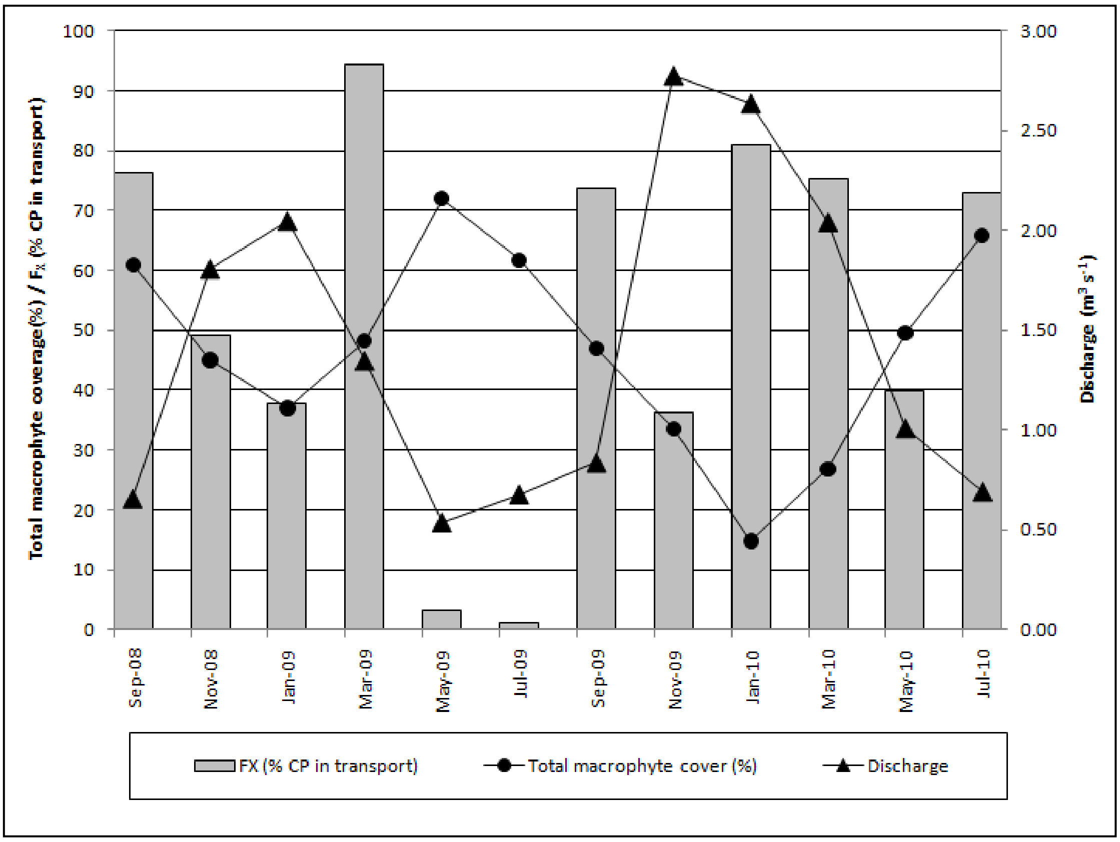


Figure 5.7 – The transport efficiency (F_X) within seasonal releases with corresponding changes in total macrophyte area cover (%) and discharge ($m^3 s^{-1}$) between September 2008 and July 2010 at Frome Vauchurch on the River Frome.

in F_X corresponded greatly with increases in macrophyte cover from 50 to 66 % respectively, as well as a decrease in discharge from 1.01 to 0.69 $m^3 s^{-1}$ and lower values for mean flow velocity and mean total depth.

5.1.2.2 Seasonal changes in longitudinal loss rate (K_P)

There were no apparent relationship between K_P and corresponding changes of total macrophyte cover within the two year dataset (Figure 5.8). Values of K_P appeared to increase slightly between experimental releases from September 2008 to the release in January 2009, with values of K_P for September 2008, November 2008 and January 2009 being 0.009, 0.024 and 0.032 m^{-1} respectively. K_P decreased considerably in the March 2009 release to 0.002 m^{-1} corresponding with an increase in F_X between January 2009 and March 2009. The value for K_P in March 2009 was the least of the whole dataset on the Frome. In May 2009 and July 2009 K_P values had increased considerably to 0.116 and 0.147 m^{-1} accordingly, which was the result of higher values of F_X in both of those months. The value of K_P in September 2009 then decreased notably (0.010 m^{-1}), prior to an increase of K_P in the November 2009 release to 0.034 m^{-1}. A further lower value of K_P then occurred in the January 2010 release of 0.007

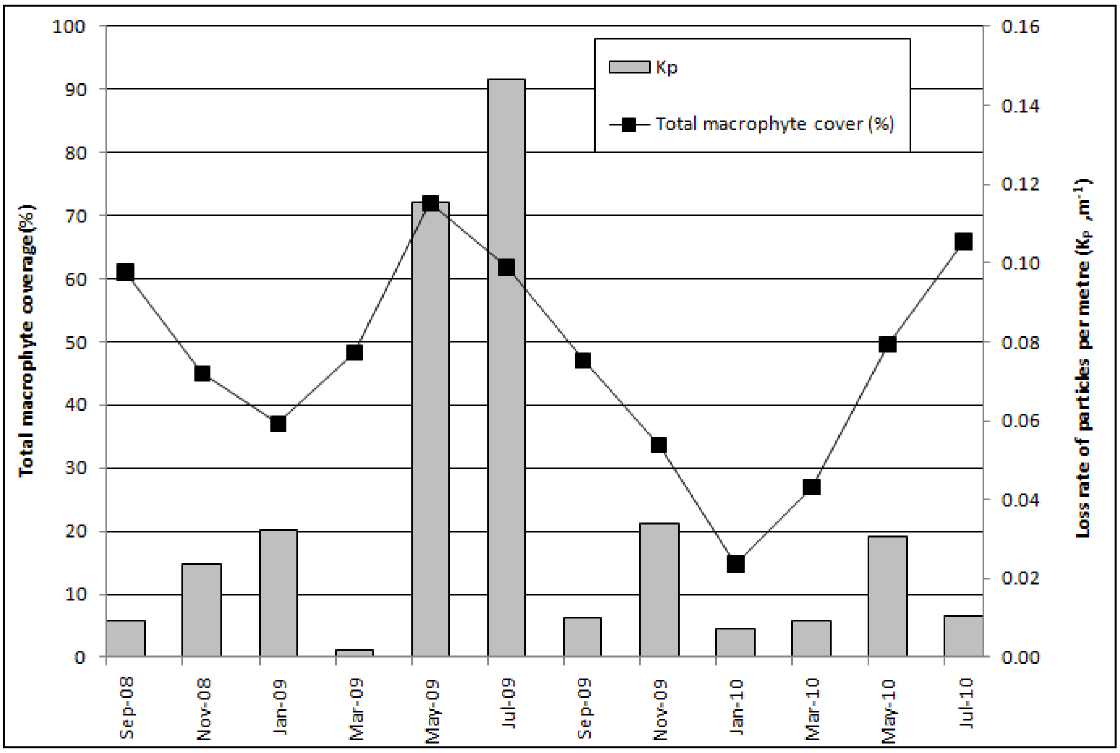


Figure 5.8 – Changes in the longitudinal loss rate (K_P, m^{-1}) of corn pollen from the seasonal releases and corresponding changes in total macrophyte cover at Frome Vauchurch on the River Frome between September 2008 and July 2010.

m^{-1}. Values of K_P remained considerably low between January 2010 and March 2010 with there being little difference in K_P between the two releases. K_P then increased from 0.009 to 0.031 m^{-1} between March 2010 and May 2010, before decreasing to 0.011 m^{-1} in July 2010.

5.1.2.3 Seasonal changes in mean transport distance (S_p)

There appeared to be no relationship between S_P and total macrophyte cover in the two year dataset (Figure 5.9). S_P decreased from 111 to 31 m from September 2008 to January 2009 correspondingly. The greatest value of S_P occurred in March 2009, where the average distance travelled by corn pollen particles was estimated to be 530 m. This represents nearly 18 times the length of the initial study reach. In the releases between May 2009 and March 2010 S_P was notably lower than that of March 2009. The May and July 2009 releases had the lowest values of S_P, at 9 and 7 m respectively. This suggests that corn pollen particles within these two releases were not transported for more than one third of the length of the study reach (10 m). There was a conspicuous

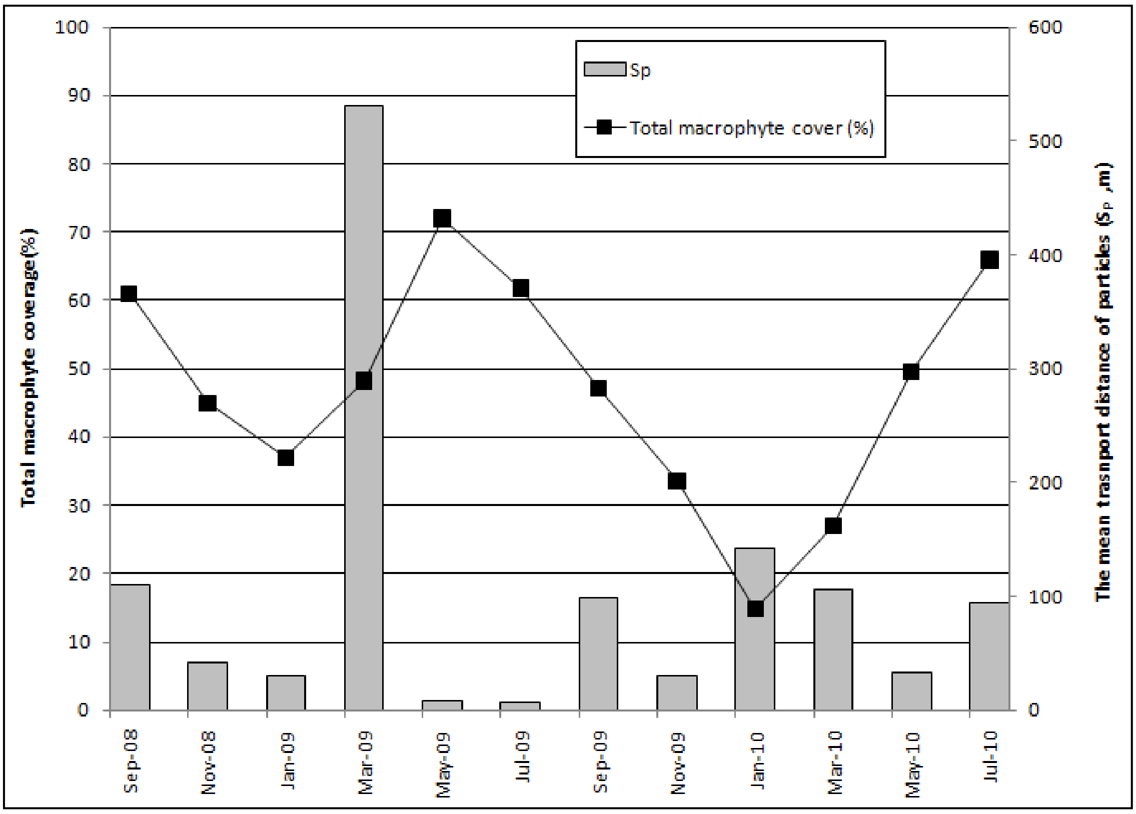


Figure 5.9 – Changes in the mean transport distance (S_P, m) of corn pollen from the seasonal releases and corresponding changes in total macrophyte cover at Frome Vauchurch on the River Frome between September 2008 and July 2010.

increase of S_P in September 2009 to 98 m, followed by a noticeable decrease in S_P in November 2009 to 30 m. The S_P in the January 2010 release had increased to 141 m or more than 4 times the length of the study reach length. S_P then subsequently decreased to 106 and 33 m in March 2010 and May 2010 respectively, before a further increase to 95 m in July 2010.

5.1.2.4 Seasonal changes in mean time of particles in suspension (T)

No clear relationship was found between the seasonal values of T in experimental releases and total macrophyte cover (Figure 5.10). T decreased considerably between September 2008 and January 2009, starting at 540 s before decreasing to 88 s respectively. In the March 2009 release T had increased considerably to 1630 s. This was the greatest amount of time that corn pollen had remained suspended in the water column for the entire Frome Vauchurch dataset, and exceeded that of the Bere Stream results. The subsequent releases in May and July 2009 revealed that corn pollen particles spent less than one minute in suspension. The value of T in July 2009 was the

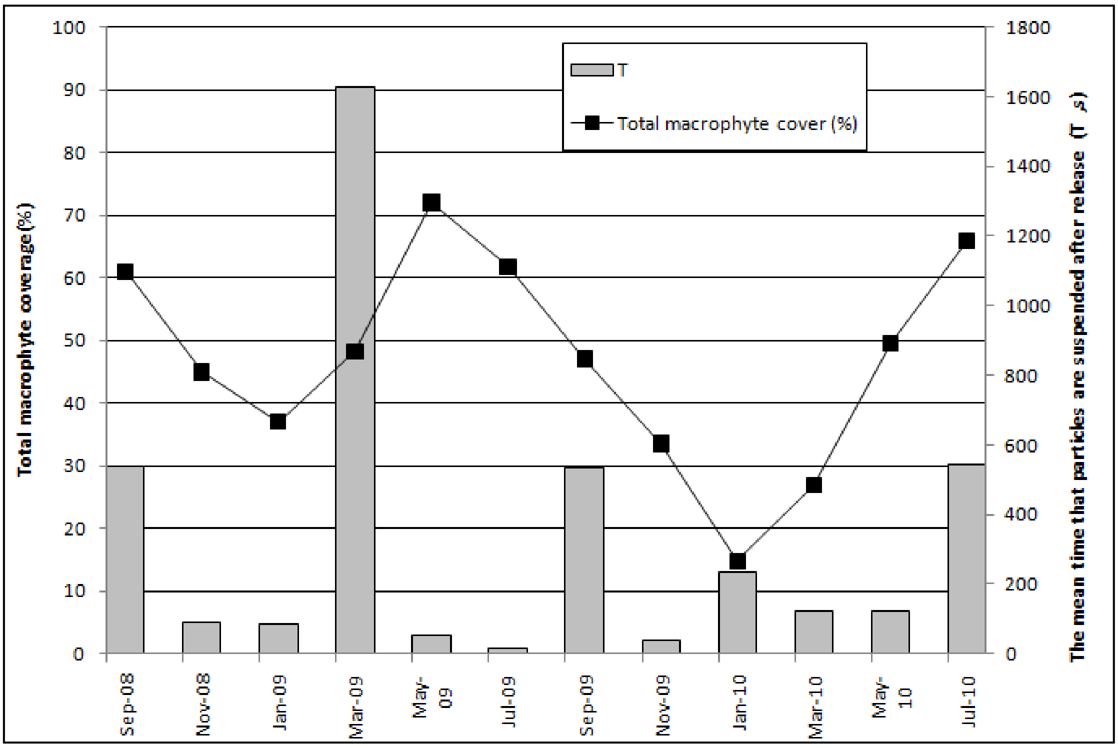


Figure 5.10 – Changes of the mean time that corn pollen remained suspended (T, s) within each seasonal release and corresponding changes in total macrophyte cover at Frome Vauchurch on the River Frome between September 2008 and July 2010.

lowest value in the entire dataset at 15 s, and the value of T in the September 2009 release was the third highest in the dataset at 534 s. In the releases following September 2009 the value of T were considerably lower at 161 and 234 s in November 2009 and January 2010 respectively. The two releases in March 2010 and May 2010 had the same estimate values of T at 123 s. The estimated value of T had increased in July 2010 to 543 s, which was comparable with the release in July 2009.

5.1.2.5 Seasonal changes in deposition velocity (V_{dep})

The values of V_{dep} and K_P from the experimental releases at Frome Vauchurch show a similar pattern throughout the seasonal releases (Figure 5.11), but with different units. The value of V_{dep} from the release in September 2008 was 0.68 mm s^{-1}. The values of V_{dep} in November 2008 and January 2009 increased conspicuously to 5.00 and 5.31 mm s^{-1} correspondingly. V_{dep} was least in March 2009 (0.29 mm s^{-1}) coinciding with the highest value for F_X and S_P, and the lowest of K_P within the dataset. V_{dep} increased in May 2009 and July 2009 to 7.78 and 32.33 mm s^{-1} respectively, which corresponded

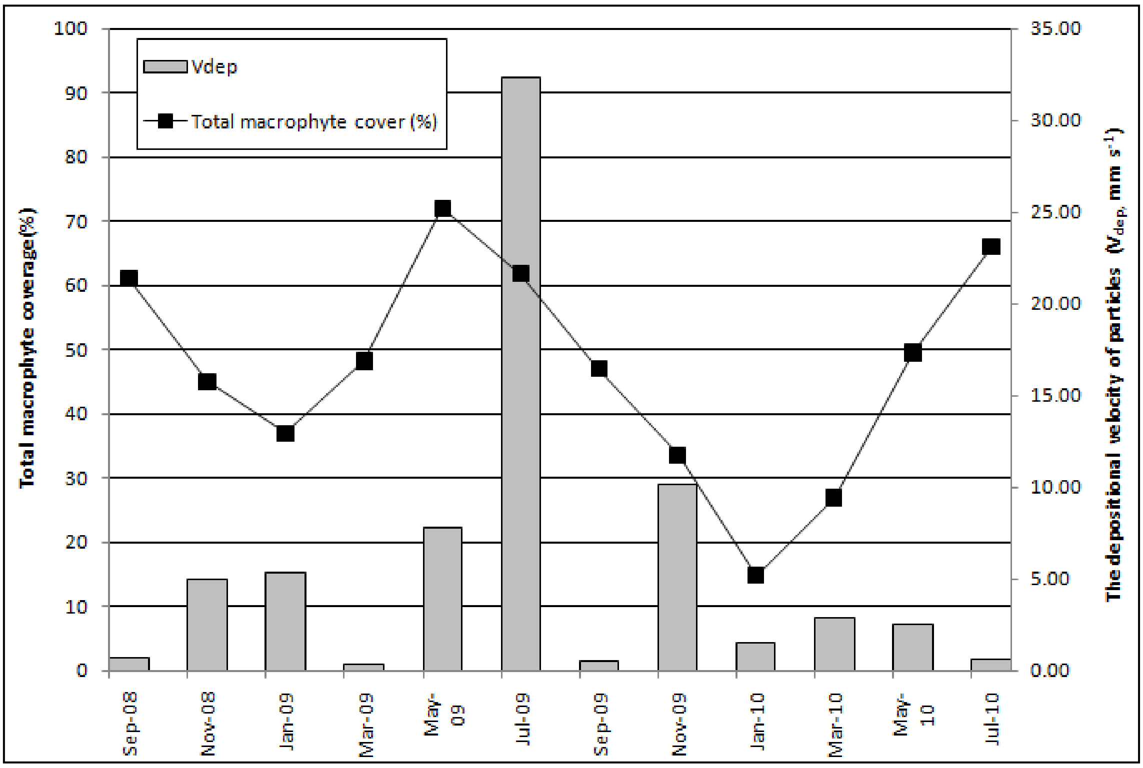


Figure 5.11 – The values of particle deposition velocity (V_{dep}, mm s^{-1}) within each seasonal release and corresponding changes in total macrophyte cover at Frome Vauchurch on the River Frome between September 2008 and July 2010.

with the highest cover of macrophytes within the reach. The release in July 2009 had the highest value of V_{dep} in the whole dataset, and therefore the greatest particle deposition velocity of all the releases at Frome Vauchurch. In September 2009, November 2009 and January 2010 the values of V_{dep} changed noticeably from 0.54 to 2.45 mm s^{-1} and finally to 1.56 mm s^{-1}. The change in V_{dep} values between September 2009 and January 2009 coincided with similar magnitudes of change in mean channel depth from 0.29 to 0.39 to 0.36 m, and discharge from 0.84 to 2.78 to 2.64 $m^3 s^{-1}$.

The value of V_{dep} increased to 2.84 mm s^{-1} in the March 2010 release. There was subsequent little change between March 2010 and May 2010 (2.49 mm s^{-1}), but V_{dep} was greater in July 2010 at 0.58 mm s^{-1}.

5.1.2.6 Statistical analyses of release parameters in Frome Vauchurch releases

A Pearson Product-Moment correlation analysis (Table 5.4) was used to explore linear correlations between the ecological, geomorphological and hydrological variables measured within the channel during each release. The significance of the correlation was assessed using the correlation coefficient ***r*** and ***P***-values as previously discussed with the Bere Stream data (see section 5.1.1.6).

There were no significant correlations between F_X and the other parameters. Values of Manning's N (-0.43, ***P*** = 0.16) and *Ranunculus* area cover (***r*** -0.45, ***P*** = 0.14) were close to being significantly correlated to corresponding values of F_X. Values of Manning's N were significantly correlated to corresponding values of total vegetation cover (0.82, ***P*** <0.01) and *Ranunculus* cover (0.83, ***P*** <0.01).

Values of K_P were only significantly correlated with corresponding values for Manning's N (***r*** 0.61, ***P*** = 0.04). Values of both T and V_{dep} were not significantly correlated to any other corresponding values from any of the parameters.

5.1.2.7 Summary of reach scale experimental releases on the River Frome

Seasonal variations in total macrophyte cover and *Ranunculus* cover were not linearly correlated with values of F_X, K_P, S_P, V_{dep} or T for released corn pollen particles. This suggests there were no interaction between seasonal variations in total macrophyte cover or *Ranunculus* cover and the transport of fine sediment within channel at Frome

Vauchurch. The only possible link between the two is the highly significant correlations that were found between channel roughness in the form of values of Manning's N and K_P. Values of K_P may have been indirectly impacted by the interaction of total vegetation cover and due to its implied affect on channel roughness as indicated by Manning's N values.

Values of F_X, S_P, T were lowest and values of K_P were highest in May 2009 and July 2009. This corresponded with the greatest total macrophyte area cover and *Ranunculus* area cover in addition to notably decreased discharge and considerably high Manning's N values. Values of F_X, S_P and T were noticeably greater and values of K_P and V_{dep} were least when total macrophyte cover was between 15 and 48 % combined with discharge values between 0.84 and 2.64 m^3 s^{-1}. It was also found that decreasing values of F_X directly corresponded to decreasing values of mean total depth within the months of March 2009, September 2009, January 2010 and March 2010.

Table 5.4 - The results matrix from a Pearson Product-Moment correlation analysis of the release parameters from analogue particle releases on the reach at Frome Vauchurch on the River Frome. To indicate the strength of each correlation there is a correlation coefficient value or *r* value and an associated statistical significance (*P* value) with 10 degrees of freedom (*d.f.*).The significant of the correlation is assessed at an alpha level of 0.05. High *r* correlation values and significant *P*-values are highlighted. F_X –particle transport efficiency, TV % cover - total vegetation % cover, R % cover – *Ranunculus* % cover, MV % cover – marginal vegetation % cover, Q – discharge, u – mean channel velocity, h – mean channel depth (from the waters' surface), NTT – nominal transport time, CW – mean channel width, W: D – Width to depth Width to depth ratio, K_P – longitudinal loss rate, V_{dep} – depositional velocity, T – average time in suspension, Manning's –Manning's N number of the channel, Re - Reynolds number of the channel, and Shear stress – Channel shear stress (N/m^2). AC in the results matrix indicates that result values were not added because of autocorrelation.

		F_X	TV % cover	R % cover	MV % cover	u	Q	h	NTT	CW	W:D	S_P	K_P	V_{dep}	T
TV % cover	***r***	-0.398													
	P	0.200													
R % cover	***r***	-0.448	**0.985**												
	P	0.144	**0.000**												
MV % cover	***r***	0.025	0.576	0.425											
	P	0.939	0.050	0.169											
u	***r***	0.057	**-0.751**	**-0.732**	-0.466										
	P	0.860	**0.005**	**0.007**	0.126										
Q	***r***	0.201	**-0.903**	**-0.858**	**-0.669**	**0.801**									
	P	0.531	**0.000**	**0.000**	**0.017**	**0.002**									
h	***r***	-0.363	0.060	0.156	-0.438	0.138	0.155								
	P	0.246	0.852	0.629	0.155	0.670	0.631								
NTT	***r***	-0.037	**0.763**	**0.737**	**0.517**	**-0.904**	**-0.803**	-0.369							
	P	0.909	**0.004**	**0.006**	0.085	**0.000**	**0.002**	0.238							
CW	***r***	0.046	**-0.606**	-0.478	**-0.898**	0.491	**0.589**	0.408	-0.505						
	P	0.888	**0.037**	0.116	**0.000**	0.105	**0.044**	0.188	0.094						
W:D	***r***	0.375	-0.081	-0.173	0.410	-0.158	-0.164	**-0.989**	0.366	-0.350					
	P	0.230	0.802	0.591	0.186	0.623	0.610	**0.000**	0.242	0.264					
S_P	***r***	AC	-0.112	-0.072	-0.252	-0.058	0.029	0.208	-0.051	0.338	-0.161				
	P		0.729	0.825	0.429	0.859	0.930	0.516	0.876	0.282	0.617				
K_P	***r***	AC	0.497	0.542	0.050	-0.099	-0.377	0.432	0.082	-0.005	-0.434	AC			
	P		0.100	0.069	0.878	0.759	0.227	0.161	0.801	0.989	0.159				
V_{dep}	***r***	AC	0.242	0.244	0.113	0.199	-0.134	0.495	-0.288	-0.043	-0.492	AC	AC		
	P		0.449	0.445	0.726	0.535	0.678	0.102	0.364	0.893	0.104				
T	***r***	AC	0.125	0.133	0.018	-0.319	-0.209	0.086	0.220	0.070	-0.041	AC	AC	AC	
	P		0.699	0.680	0.955	0.312	0.514	0.791	0.492	0.828	0.898				
Mannings N	***r***	-0.433	**0.817**	**0.832**	0.358	**-0.837**	**-0.688**	-0.051	**0.753**	-0.268	0.085	-0.096	**0.607**	0.291	0.084
	P	0.159	**0.001**	**0.001**	0.253	**0.001**	**0.013**	0.875	**0.005**	0.400	0.793	0.766	**0.036**	0.358	0.794
Re	***P***	0.195	**-0.837**	**-0.788**	**-0.660**	**0.969**	**0.795**	0.281	**-0.817**	0.555	-0.312	0.049	-0.362	-0.127	-0.194
	r	0.544	**0.001**	**0.002**	**0.020**	**0.000**	**0.002**	0.376	**0.001**	0.061	0.324	0.880	0.247	0.695	0.545
Shear stress	***r***	-0.224	-0.210	-0.056	**-0.830**	0.427	0.288	**0.805**	-0.413	**0.699**	**-0.790**	0.289	0.215	0.179	0.088
	P	0.484	0.513	0.862	**0.001**	0.167	0.364	**0.002**	0.182	**0.011**	**0.002**	0.362	0.501	0.578	0.786

5.1.3 Transport of suspended sediment loads within vegetated reaches

5.1.3.1 Estimates of fine sediment loads in transport from January 2009 to July 2010

Water samples for estimating the suspended sediment load within the survey reaches were collected within the same time period as the corn pollen releases from January 2010 to July 2010 (See Section 3.5.3). The 24 hour sample collection and subsequent analyses allowed a rudimentary estimate of mean suspended sediment load to be calculated. Values of F_X from the corn pollen releases were used to approximate the amount of sediment load that was transported through the reach.

The 'snapshot' nature of the results from this investigation was never intended to be a detailed analysis of the transport of suspended sediment load within both reaches over long periods of time. However, the outcome of this investigation allows for postulation of how channels with seasonally-changing macrophyte growth may impact the transport of suspended sediment loads. Table 5.5 illustrates the results of the suspended sediment transport analyses from January 2009 to July 2010.

The main feature that was apparent in both the Bere Stream and Frome Vauchurch datasets was the pattern in suspended sediment supply throughout the measured period. There was a weak seasonal pattern in the supply of suspended

Table 5.5 – The transport estimates of fine suspended sediment load (kg per day/ kg d^{-1}) to the upstream and downstream sections during reach scale release between January 2009 and July 2010 on the Bere Stream at Snatford Bridge (**A**) and the River Frome at Frome Vauchurch (**B**). **ST US** – Sediment load transport rate to the upstream section of the reach, **ST DS** – Sediment load transport rate to the downstream section of the reach, **MSS conc.** – Mean rate of suspended sediment over 24 hours, **CP transport (%)** - % of corn pollen transported from the upstream section to the downstream section of the reach, and **Q** – Discharge.

		Jan-09	Mar-09	May-09	Jul-09	Sep-09	Nov-09	Jan-10	Mar-10	May-10	Jul-10
A	ST US (kg d^{-1})	8251	470	123	274	283	2334	2720	1533	436	99
	ST DS (kg d^{-1})	2970	378	33	96	244	2240	2502	797	397	65
	MSS conc. (mg/L^{-1})	7	9	4	7	7	26	20	23	9	4
	CP transport (%)	32	80	27	35	86	96	92	52	91	66
	Q (L S^{-1})	581	593	332	439	499	1043	1562	787	544	319
B	ST US (kg d^{-1})	12030	7949	757	1564	421	8251	1778	6210	357	357
	ST DS (kg d^{-1})	4571	7472	23	16	311	2970	1440	4658	143	143
	MSS conc. (mg/L^{-1})	68	68	16	27	6	34	8	35	4	4
	CP transport (%)	38	94	3	1	74	36	81	75	40	40
	Q (L S^{-1})	2050	1351	542	682	839	2782	2640	2044	1012	1012

day (kg d^{-1}) in January 2010 on the Bere Stream, in comparison with 12030 kg d^{-1} on Frome Vauchurch in January 2009. The least inputs of suspended sediment to the top of the reach at the Bere Stream and Frome Vauchurch reach was in July 2010, at 99 kg d^{-1} and 177 kg d^{-1} correspondingly.

On the Bere Stream there was a seasonal pattern of suspended fine sediment transport to the top and bottom of the reach (Figure 5.12). Higher suspended sediment concentrations were present in January 2009 and from November 2009 to March 2010, in comparison to months between May 2009 and September 2009 as well as July 2010. There appeared to be very little difference in between suspended sediment input to the top and bottom of the reach during the entire measured period in comparison to Frome Vauchurch. Suspended sediment transport on the reach at Frome Vauchurch was more variable between the top and bottom compared to the Bere Stream. The data in January 2009 were similar to the Bere Stream in terms of the difference in suspended sediment input between the top and bottom of the reach. There was a seasonal pattern present within the dataset with higher sediment concentrations from January 2009 to May 2009, also September 2009 and May 2010. The Frome Vauchurch reach experienced considerably less sediment being transported from May 2009 to September 2009 and May 2010 to July 2010.

5.1.3.2 The characteristics of the suspended sediment sampled in September 2009

The physical characteristics of the sampled suspended sediment from September 2009 are illustrated in Table 5.6. This was only a snapshot and the results cannot be regarded as definitive of all suspended sediment that was in transport during the study period because of the variable nature of suspended sediment supply and content (Walling and Moorehead, 1989). However, it does provide insight into the physical characteristics of the suspended sediment within the two study streams.

In both reaches, organic matter comprised approximately 25 % of the suspended sediment. The median particle size of effective sediments was smaller compared with absolute samples, being within the coarse silts at 44 and 59 μm in Frome Vauchurch and Bere Stream respectively. The absolute sample from the Bere Stream had a larger median particle size in comparison with the sediment from Frome Vauchurch at 102 µm (very fine sand) and 52 µm (coarse silt) correspondingly. It appeared that the organic constituents within the suspended sediment made up a sizeable proportion of the smaller particles in both streams, possibly contributing to

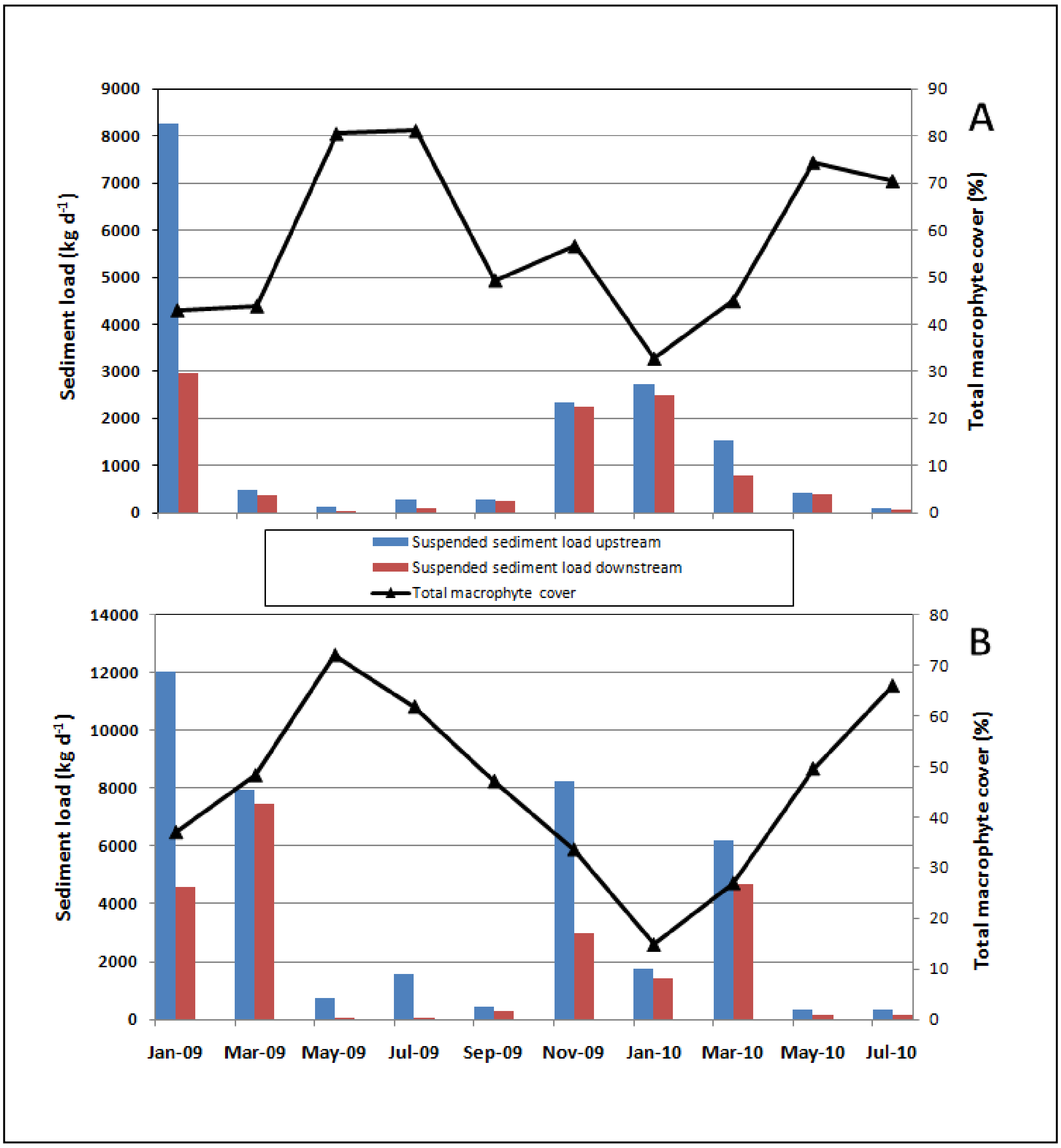


Figure 5.12 – Suspended sediment load transport (kg d^{-1}) estimates to the upstream and downstream sections of the reach at (A) the Bere Stream at Snatford Bridge and (B) the River Frome at Frome Vauchurch between January 2009 and July 2010.

flocculation. More than half of the sample volume was composed of silt and clay particles in absolute suspended sediment samples from both sites, and the effective sample from the Frome Vauchurch (Figure 5.13). The effective sample from the Bere Stream was composed of more sand–sized particles (>63 µm) which comprised 68 % of the sample volume.

Table 5.6 - The physical and chemical characteristics of suspended sediment particles sampled during September 2009 from the Bere Stream at Snatford Bridge and the River Frome at Frome Vauchurch. **BD** – dry bulk density.

	Frome Vauchurch	Bere Stream
BD (kg m^{-3})	407	239
Organic matter %	25	25
Absolute median particle size (µm)	51.5	102.2
Effective median particle size (µm)	43.8	58.8

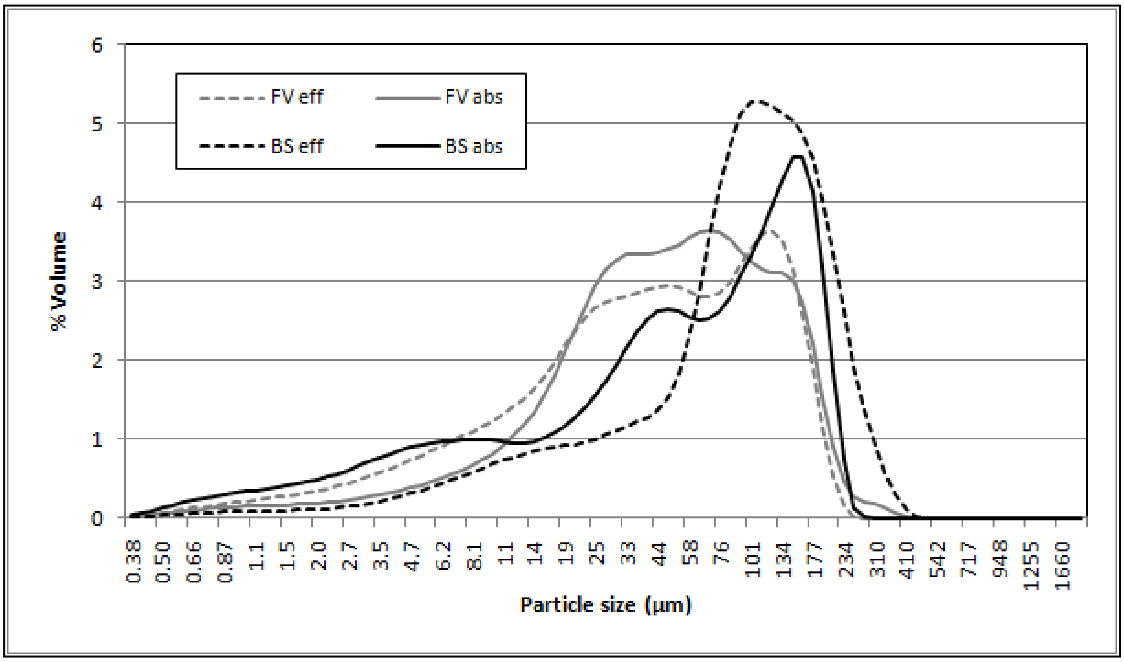


Figure 5.13 – The particle size (µm) distributions of effective (eff) and absolute (abs) suspended sediment fractions sampled from the Bere Stream at Snatford Bridge (BS) and the River Frome and Frome Vauchurch (FV) during the September 2009 survey month.

5.1.4 Interactions between fine sediment transport and channel porosity associated with changing macrophyte growth

A measure of channel porosity (φ) was calculated from survey data collected between July 2008 and July 2010 at both the Bere Stream and Frome Vauchurch study sites. Porosity was estimated as a measure of the 'leakiness' or amount of high velocity water flowing within the channel around in-stream vegetation. Details of the calculations and values of porosity are given in Section 3.10.

5.1.4.1 Absolute plant volume calibration curve

Absolute plant volume was measured from the five *Ranunculus* plants taken from both field sites (see section 3.10.2 for methods). A rudimentary calibration curve was constructed between the absolute and composite plant volumes as illustrated in Figure 5.14. The r^2 value of the curve ($r^2 = 0.92$) revealed there was a significant relationship

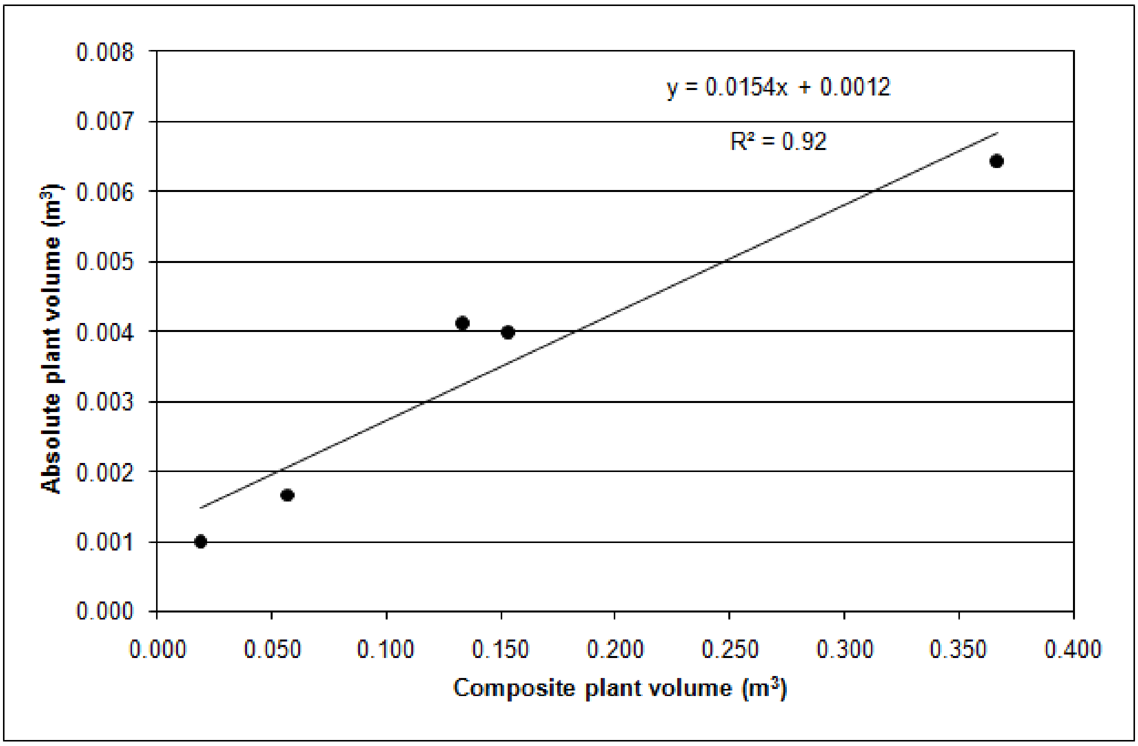


Figure 5.14 – The *Ranunculus* volume calibration curve illustrating a linear regression between the composite plant volume (m^3) and absolute plant volume (m^3) from the five plants. Composite plant volume is the estimated volume of plant matter and water together, whilst the absolute plant volume is the estimated volume of plant matter only.

between absolute and composite plant volume. The resulting equation of the curve was used to convert composite *Ranunculus* volumes calculated from reach scale data by the GIS.

5.1.4.2 Channel porosity on the Bere Stream

The changes in channel porosity and total vegetation cover were measured over two annual cycles (Figure 5.15), total vegetation cover included marginal and in-channel macrophytes. There appeared to be a seasonal pattern of channel porosity within the reach that corresponded with changes in discharge and the total vegetation cover.

Channel porosity was low between July 2008 and December 2008. There was a decrease in porosity between July 2008 (φ 0.36) and September 2008 (φ 0.20), followed by an increase in March 2009 (φ 0.69), which was the greatest value of porosity between July 2008 and July 2009. There was a noticeable decrease in porosity in December 2008 (φ 0.17). This was possibly due to the proportion of submerged and emergent *Ranunculus* changing within the reach. The percentage of submerged *Ranunculus* cover changed from 74 to 41 % and then to 55 % in November 2008, December 2008 and January 2009 respectively. In the same period, discharge had

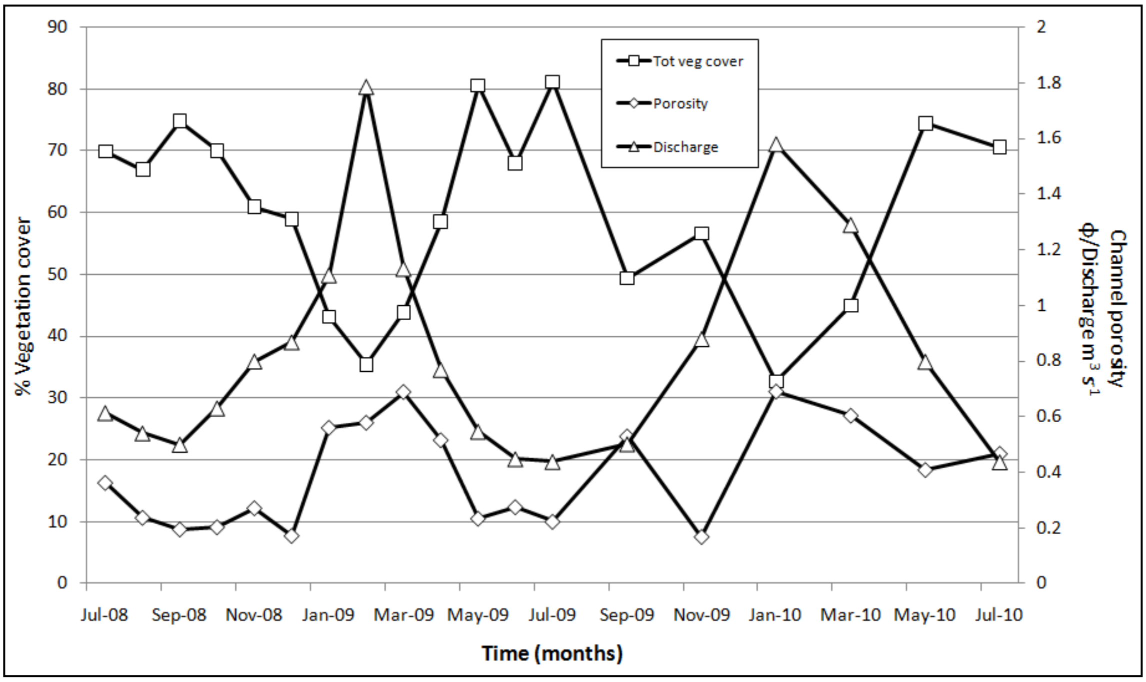


Figure 5.15 – The changes in discharge (m^3 s^{-1}) channel porosity (φ) and total vegetation cover (%) on the Bere Stream at Snatford Bridge over the two year survey period between July 2008 and July 2010.

gradually decreased from 0.61 $m^3 s^{-1}$ in July 2008 to 0.50 $m^3 s^{-1}$ in September 2008, this was followed by a noticeable increase of discharge in February 2009 (1.78 $m^3 s^{-1}$). Detailed analysis on the changes of vegetation cover over this period has already been discussed in Section 4.1.1.

The total vegetation cover increased from July 2008 to September 2008 (70 and 75 % respectively) followed by a decrease through to February 2009 (35 %). *Nasturtium* had been the dominant macrophyte throughout this period, with the peak in cover occurring during September 2008 at 55 %, and a subsequent decrease to 3 % in April 2009. The macrophyte cover maps (see section 4.1.2) of this period indicate that *Nasturtium* had encroached into the centre of the stream in August 2008, and was subsequently restricted to the margins in the months after.

Following March 2009 porosity declined and remained low between May 2009 (φ 0.22) and July 2009 (φ 0.22). There was a small increase in June 2009 (φ 0.28) which was possibly due to a decrease in total vegetation cover. This in turn was influenced in the most part by a notable decrease in *Ranunculus* cover from 50 to 28 % in May 2009 and June 2009 correspondingly. Macrophyte cover maps showed that the loss of *Ranunculus* occurred with an increase in marginal emergent vegetation cover mostly comprising of *Apium* which encroached from the banks. Discharge also decreased to 0.43 $m^3 s^{-1}$ in July 2009.

Following July 2009, the datasets were produced in bimonthly snapshots with September 2009 being the subsequent sample month. Porosity had increased notably in between July 2009 and September 2009 from φ 0.22 to φ 0.53 respectively, followed by a decrease to φ 0.17 in November 2009 before a subsequent increase again to φ 0.69 in January 2010. Discharge had also increased between July 2009 and September 2009 from 0.44 to 0.88 $m^3 s^{-1}$. The total vegetation cover appeared to be the single factor that affected the channel porosity during this period. From July 2009 to September 2009 total vegetation cover decreased from 81 to 49 % correspondingly. In this period both *Ranunculus* and *Nasturtium* had decreased in cover. Total vegetation cover increased between September 2009 and November 2009. The increase in cover comprised of gains in *Nasturtium* to 24 % and persisting cover of marginal emergent vegetation that was primarily composed of *Apium.* Porosity increased considerably in January 2010 to the greatest value within the second survey year following the removal of *Apium* and *Nasturtium* by increasing winter discharges.

Between January 2010 and July 2010 changes in porosity and the total vegetation cover followed a similar pattern. There was a gradual decrease in discharge between January 2010 and May 2010 from 1.58 to 0.80 $m^3 s^{-1}$ correspondingly, which was followed by a large decrease to 0.44 $m^3 s^{-1}$ in July 2010. Total vegetation cover increased between January 2010 and May 2010 from 33 to 74 %, with *Ranunculus* being the main component of change. There was a decrease in total vegetation cover between May 2010 and July 2010 due to considerable losses of *Ranunculus* cover and notable increases in the cover of *Apium.* Porosity within the channel decreased between January 2010 and March 2010 from φ 0.69 to φ 0.60. The ratio of submergent and emergent *Ranunculus* had changed during this period from 99 % of the *Ranunculus* being submergent in January 2010 to only 43 % in March 2010. Channel porosity then decreased to φ 0.41 in May 2010 before increasing to φ 0.47 in July 2010. This corresponded with an increase in total vegetation cover in May 2010 to 74 % and a subsequent slight decrease to 71 % in July 2010.

5.1.4.3 Statistical analyses of Bere Stream channel porosity data

The datasets in Figure 5.15 suggest the possibility of a high correlation between channel porosity and total vegetation cover. A Pearson Product-Moment correlation was used to analyse how well linearly correlated the channel porosity data was with macrophyte area cover and absolute volume data (Table 5.7).

The results suggest that values of total vegetation cover and corresponding channel porosity values were highly correlated and significant (***r*** -0.76, ***P*** <0.001). *Nasturtium* cover were significantly correlated with channel porosity (***r*** -0.67, ***P*** = 0.002), while *Ranunculus* cover values were not significantly correlated. The results suggest that increases in *Nasturtium* cover resulted in decreases in channel porosity, rather than corresponding increases in *Ranunculus* cover.

Channel porosity values and analogous values of total vegetation volume were highly negatively correlated and significant (***r*** -0.92, ***P*** <0.001). The volume of *Nasturtium* was the main component within the total vegetated volume that was highly correlated with the channel porosity and significant (***r*** -0.62, ***P*** = 0.005). In comparison, values of *Ranunculus* absolute volume were not significantly correlated with corresponding values of channel porosity. Values of discharge were significantly correlated with channel porosity (***r*** 0.65, ***P*** = 0.002), as was mean channel water velocity (m s^{-1}) (***r*** 0.54, ***P*** = 0.02).

Channel porosity values were significantly correlated with channel Reynolds number values (***r*** 0.52, ***P*** = 0.02), suggesting that increases in channel porosity were related to increases in turbulent flow within the channel.

Table 5.7 – The results of the correlation analysis between hydrological, geomorphological and ecological parameters and channel porosity from the Bere Stream at Snatford Bridge. Values of ***r*** indicate the correlation coefficient and ***P*** as the *P* value with 11 degrees of freedom (*d.f.*). Significant ***r*** values and *P* values are highlighted in bold, with *P* values significant to an alpha value of 0.05.

	Channel porosity ϕ	
	r	***P***
Total vegetation cover (%)	**-0.76**	**<0.001**
***Ranunculus* cover (%)**	0.29	0.23
***Nasturtium* cover (%)**	**-0.67**	**0.002**
Marginal vegetation (%)	-0.26	0.29
Channel discharge (m^3 s^{-1})	**0.65**	**0.002**
Mean channel width (m)	0.34	0.16
Mean channel depth (m)	0.33	0.17
Mean channel velocity (m s^{-1})	**0.54**	**0.02**
Total vegetation volume (m^3)	**-0.92**	**<0.001**
***Ranunculus* absolute volume (m^3)**	0.42	0.07
***Nasturtium* volume (m^3)**	**-0.62**	**0.005**
Channel Reynolds number, Re	**0.52**	**0.02**
Manning's N	0.45	0.05
Channel Shear stress (N/m^2)	0.24	0.32

5.1.4.4 Channel porosity and corn pollen release parameters from the Bere Stream

An additional Pearson Product-Moment correlation was used to analyse the correlation between channel porosity and parameters from the corn pollen release data (Table 5.8). Channel porosity values were not significantly correlated to values of any of the five parameters from the corn pollen releases on the Bere Stream. This suggests that variations in channel porosity did not impact the transport of corn pollen within the seasonal releases on the Bere Stream.

Table 5.8 – A table illustrating the results of the correlation analysis between corn pollen parameters from seasonal releases including F_X, S_P, K_P, V_{dep}, T and corresponding values of channel porosity. ***r*** is the correlation coefficient and ***P*** is the associated *P* value. Values of ***r*** indicate the correlation coefficient and ***P*** is the associated *P* value with 11 degrees of freedom (*d.f.*). Significant ***r*** values and *P* values are highlighted in bold, with *P* values significant to an alpha value of 0.05.

	Channel porosity ϕ	
	r	***P***
Transport efficiency (Fx, %)	0.35	0.24
Mean transport distance (Sp, m)	-0.09	0.77
Longitudinal loss rate (K_P, m^{-1})	-0.39	0.18
Depositional velocity (V_{dep}, mm s^{-1})	-0.25	0.40
Mean time in suspension (T, s)	-0.03	0.92

5.1.4.5 Channel porosity on Frome Vauchurch

The changes in channel porosity and total vegetation cover were analysed over two annual cycles of macrophyte growth (Figure 5.16). Total macrophyte cover comprised mainly of *Ranunculus* for the duration of the survey period (See Section 4.1.4). Channel porosity at Frome Vauchurch had a weak seasonal pattern in the period that was analysed. The seasonal pattern was not as conspicuous as that observed on the Bere Stream during the same period. But it was possible to observe decreases in channel porosity between summer and early autumn months, examples included between July 2008 and October 2008 and between May 2009 and September 2009. The changes in channel porosity and total vegetation cover were analysed over two annual cycles of macrophyte growth (Figure 5.16). Total macrophyte cover comprised mainly of *Ranunculus* for the duration of the survey period (See Section 4.1.4). Channel porosity at Frome Vauchurch had a weak seasonal pattern in the period that was analysed. The seasonal pattern was not as conspicuous as that observed on the Bere Stream during the same period. But it was possible to observe decreases in channel

Channel porosity had decreased from July 2008 to September 2008 (φ 0.64 to φ 0.55 correspondingly). From September 2008 channel porosity increased to φ 0.70 in January 2009. In the same period total macrophyte cover was seen to decrease initially between July 2008 and August 2008 (62 and 56 % respectively) followed by a small increase in cover in September 2008 to 61 %. During the following months after September 2008 there was a decrease in cover to 37 % in January 2009. The increase of total vegetation cover in September 2008 was mostly due to the increasing cover of marginal riparian vegetation that encroached into the channel from the left bank, and a small increase in *Ranunculus* cover. Discharge increased notably from July 2008 to January 2010, 0.66 to 2.05 $m^3 s^{-1}$ correspondingly, with a decrease in discharge between November 2008 to December 2008. Due to the flashy nature of the hydrology within the

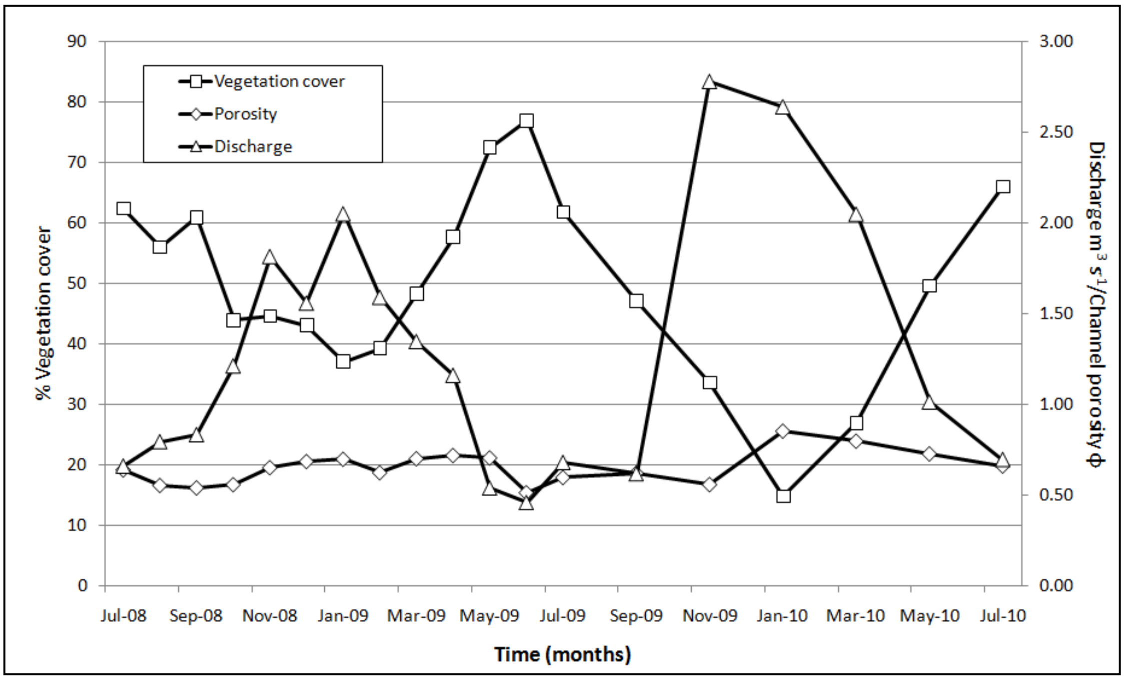


Figure 5.16 – The changes in discharge ($m^3 s^{-1}$) channel porosity (φ) and total vegetation cover (%) on the River Frome at Frome Vauchurch over the two year survey period between July 2008 and July 2010.

Frome Vauchurch channel, it is possible that the discharge measurement in November 2009 may have been unusually high when it was recorded (See Section 4.1.8.2).

Channel porosity between January 2009 and May 2009 remained fairly stable, between φ 0.70 and φ 0.72 excluding February 2009 where channel porosity decreased noticeably to φ 0.62. Between January 2009 and February 2009 the channel discharge had started to decline, eventually decreasing to 0.46 $m^3 s^{-1}$ in June 2009. There was an increase in total macrophyte cover starting from January 2009 to the peak in cover recorded in June 2009 at 77 %, this was comprised mostly of *Ranunculus* cover but also included smaller increases in marginal vegetation cover. The increase of total vegetated cover between May 2009 and June 2009 from 72 to 77 % correspondingly was caused by an increase in marginal riparian vegetation cover. *Ranunculus* cover remained at 69 % in both months. In June 2009 *Ranunculus* stands appeared to overlap one another creating a larger blockage to the incoming flow of water. The increase in total vegetation cover also coincided with a decrease in discharge, leading to a significant decrease in channel porosity from φ 0.70 to φ 0.51 in May 2009 and June 2009 correspondingly.

From June 2009 total vegetation cover decreased to just 15 % in January 2010. Discharge started to increase from June 2009, increasing to a peak of 2.78 $m^3 s^{-1}$ in November 2009. There was a subsequent slight decrease in discharge between November 2008 and January 2010 to 2.64 $m^3 s^{-1}$. Channel porosity generally increased from June 2009 corresponding with decreases in the total vegetation cover and increases in discharge. Channel porosity peaked at φ 0.85 in January 2010. This decline in channel porosity coincided with a loss in marginal riparian vegetation encroaching from the banks into the stream, cover declined from 10 to just 5 % in September 2009 and November 2009 correspondingly.

Channel porosity decreased gradually from φ 0.85 to φ 0.66 between January 2010 and July 2010 respectively. This occurred with proportional increases in total vegetation cover from 15 % in January 2010 to 66 % in July 2010.

5.1.4.6 Statistical analyses of Frome Vauchurch channel porosity data

The data illustrated in Figure 5.16 suggested the possibility of a correlation between the calculated channel porosity and total vegetated cover over the two year survey period. A

Pearson Product-Moment correlation was used to determine if ecological, hydrological and geomorphological data were linearly correlated with the channel porosity data (Table 5.9).

Channel porosity and total vegetation cover in Frome Vauchurch had a significant negative correlation (***r*** -0.53, ***P*** = 0.02), and *Ranunculus* cover was also significantly correlated with channel porosity (***r*** -0.47, ***P*** = 0.04). This suggests that increases in total macrophyte cover and particularly *Ranunculus* cover were associated with corresponding decreases in channel porosity in Frome Vauchurch during the surveyed period. A correlation analysis performed between channel porosity and the total vegetation volume and *Ranunculus* absolute volume (m^3) indicated that channel porosity was highly significantly correlated with total vegetation volume (***r*** -0.86, ***P*** <0.001) and *Ranunculus* absolute volume (***r*** -0.48, ***P*** = 0.04). This suggests that increases in total vegetation volume and in particular *Ranunculus* absolute volume were highly associated with decreases in channel porosity. Discharge was found to be non-significantly correlated with channel porosity (***r*** 0.43, ***P*** = 0.07). This suggested that increases in channel porosity values were not associated with increases in channel discharge values at Frome Vauchurch.

Table 5.9 – A matrix illustrating the results of the correlation analysis of hydrological, geomorphological and ecological parameters with channel porosity from the River Frome at Frome Vauchurch. Values of ***r*** indicate the correlation coefficient and ***P*** is the associated *P* value with 10 degrees of freedom (*d.f.*). Significant ***r*** values and *P* values are highlighted in bold, with *P* values significant to an alpha value of 0.05.

	Channel porosity φ	
	r	*P*
Total vegetation cover (%)	**-0.53**	**0.02**
Ranunculus cover (%)	**-0.47**	**0.04**
Marginal vegetation (%)	-0.33	0.17
Channel discharge ($m^3 s^{-1}$)	0.43	0.07
Mean channel width (m)	0.43	0.07
Mean channel depth (m)	-0.09	0.70
Mean channel velocity ($m s^{-1}$)	0.42	0.08
Total vegetation volume (m^3)	**-0.86**	**<0.001**
Ranunculus absolute volume (m^3)	**-0.48**	**0.04**
Channel Reynolds number, Re	0.34	0.16
Manning's N	-0.13	0.60
Channel Shear stress (N/m^2)	0.29	0.24

5.1.4.7 Channel porosity and corn pollen release parameters from Frome Vauchurch

A Pearson Product-Moment correlation was used to determine the significance of correlation between channel porosity values and parameter values from the corn pollen releases at Frome Vauchurch (Table 4.35). Channel porosity was not significantly correlated with any of the five parameters used within corn pollen releases.

Table 4.5 – A matrix illustrating the results of the correlation analysis between F_X, S_P, K_P, V_{dep}, T and channel porosity. ***r*** is the correlation coefficient and ***P*** is the associated *P* value. Values of ***r*** indicate the correlation coefficient and ***P*** is the associated *P* value with 10 degrees of freedom (*d.f.*). Significant ***r*** values and *P* values are highlighted in bold, with *P* values significant to an alpha value of 0.05.

	Channel porosity φ	
	r	***P***
Transport efficiency (Fx, %)	0.25	0.43
Mean transport distance (Sp, m)	0.19	0.56
Longitudinal loss rate (K_P, m^{-1})	-0.21	0.51
Depositional velocity (V_{dep}, mm s^{-1})	-0.32	0.31
Mean time in suspension (T, s)	-0.03	0.94

5.2 Discussion

5.2.1 The influence of seasonally-changing macrophyte cover on fine sediment transport

This study has determined that changes in macrophyte cover do not directly correspond with seasonal variations in transport and retention of fine sediment within vegetated lowland streams that are of a stream order of 3 or less. However, the peak of macrophyte growth in the summer months (May and July 2009) at both study reaches did appear to have an impact on channel roughness, and corn pollen transport parameter values. Therefore the alternative hypothesis is accepted because seasonally changing macrophyte cover does appear to influence fine sediment transport and retention by modifying channel roughness, with a direct influence observed when total macrophyte cover is at its peak.

Increasing total macrophyte cover and *Ranunculus* cover on the Bere Stream and River Frome were not found to be significantly correlated with decreasing values of F_X and increasing values of K_P. Additionally, values of V_{dep}, S_P and T from both study sites did not appear to correspond with seasonal changes in total macrophyte cover or *Ranunculus* cover.

It was determined that seasonally changing cover and distribution of individual macrophyte species do not directly influence corresponding changes in fine sediment transport on at either sites. On this basis the second null hypothesis is accepted.

However, on the Bere Stream the second null hypothesis could be rejected as cover of marginal vegetation comprising a majority of *Apium nodiflorum* was highly correlated with values of Manning's N, which in turn was highly correlated to changing values of K_P. Therefore it could be suggested that there was an indirect influence of marginal vegetation on fine sediment deposition through changes in channel roughness. Additionally, on the River Frome the second null hypothesis could be rejected on the basis that there appears to be an interaction between seasonally changing values of *Ranunculus* cover and Manning's N values, which in turn is linked to values of K_P. Values of seasonally changing *Ranunculus* cover were highly correlated with channel roughness values in the form of Manning's N on the River Frome because *Ranunculus* cover formed the majority of total macrophyte cover within most of the two year study. Therefore it can be postulated that the variations in the cover of *Ranunculus* on the

River Frome may have had an indirect impact on the rate of fine sediment deposition due to the link between of *Ranunculus* cover and channel roughness, and values of Manning's N corresponding with values of K_P.

Changing values of channel roughness in the form of Manning's N was highly significantly correlated with variations in F_X and K_P on the Bere Stream, and with values of K_P on the River Frome. Channel roughness values were also highly correlated with seasonally changing total macrophyte cover on both sites. Therefore the results suggest that changes in macrophyte cover are not directly linked to the seasonal variability in fine sediment transport and retention within lowland rivers throughout a whole annual cycle.

But seasonal in total macrophyte cover are linked to corresponding channel roughness values, therefore it cannot be ruled out that the coverage of macrophytes has a contributory impact on variation in fine sediment transport and retention within lowland streams.

It was demonstrated that seasonally high macrophyte cover combined with low discharge values coincided with significant reductions in fine particulate sediment transport at both sites. The May 2009 and July 2009 corn pollen releases at both experimental reaches had the greatest total macrophyte cover values coupled with seasonally low values of discharge and the greatest values of Manning's N. These coincided with the lowest F_X and S_P values and greatest K_P values within the two year study period. On the Bere Stream increases in S_P were found to be significantly correlated to increases in discharge, but this was not found to be the case in releases made at Frome Vauchurch. Increased particle retention in May 2009 and July 2009 was possibly due to the impact of vegetation acting as a 'sieve' (Horvath, 2004) or physical barrier within the water column (Green, 2005c; Heppell *et al*., 2009; Sand-Jensen, 1998; Watson, 2007). Additionally, the reconfiguration of plants into wider patches during periods of lower flow velocities may have increased their efficiency in blocking the majority of the wetted channel cross section (Green, 2006).

These observations are consistent with the results of the first field releases by Warren *et al*. (2009) who found there was greater retention of corn pollen (~63 %) within the vegetated reach in comparison with the unvegetated reach during their first release. The vegetated reach in their first release had considerably high 'in-channel' macrophyte cover (78 %) coupled with low discharge (0.31 m^3 s^{-1}). Seasonally low discharge is a normal feature of UK chalk streams in the summer months (Berrie, 1992), that is often exacerbated by over-abstraction (Hearne and Armitage, 1993).

The results of the second release by Warren *et al*. (2009) indicated that the vegetated reach (63 % cover) retained marginally less corn pollen (51 % retention) in comparison with the unvegetated reach (59 % retention). The results of this current study are not totally comparable with the results of the second field release by Warren *et al*. (2009) because there was never a month in the two year observation period were either study site was completely unvegetated. Furthermore, complete absence of vegetation is most likely to occur in the winter months when there are higher values of discharge, in comparison to the lower values of discharge in the summer months. Despite this, it could be asserted that periods of low to moderate (≤ 50 %) macrophyte cover on the Bere Stream corresponded with increased values of F_X. The same relationship was not found between F_X and total macrophyte cover within the Frome Vauchurch releases, this may have been due to the total macrophyte cover being represented almost entirely by *Ranunculus* patches.

Values of S_P and T were not well correlated with total macrophyte cover, or the cover of any macrophyte at either stream site. On the reach at Frome Vauchurch nothing was correlated with S_P or T. On the Bere Stream increases in S_P and T were highly associated with increases of discharge. At the Frome Vauchurch site the primary factors influencing S_P were not identified. The mean values of S_P from releases on the Bere Stream and Frome Vauchurch in this study were 170 and 103 m correspondingly. This is considerably greater than the values for the vegetated reaches reported by Warren *et al*. (2009) of 68 m. But their releases were performed in June 2005 and July 2005 and with total macrophyte cover of 63 and 78 %. Mean values of S_P on the Bere Stream and Frome Vauchurch sites were 47 and 51 m correspondingly when they were calculated from the July release months between 2008 and 2010. These S_P values are closer and more comparative to the estimates by Warren *et al*. (2009).

The correlation coefficients between K_P and total macrophyte cover were not significant at either site. This suggested that increases in total macrophyte cover on the Bere Stream, and increases in *Ranunculus* cover at Frome Vauchurch were not directly associated with increases in corn pollen deposition, and thus fine sediment particle deposition. This agrees with the findings of work by Koetsier and McArthur (2000) who determined that CPOM transport was independent of *Sparganium* patch growth within their experimental reaches. This current study disagrees with the findings of Horvath

(2004), who concluded that increased growth of *Myosotis palustris* within his experimental releases led to decreased CPOM transport. Although, it should also be noted that the work by Koetsier & McArthur (2000) and Horvath (2004) are not directly comparable with this current study because the analogues used in their studies represented CPOM, which had purposefully different physical characteristics compared to those of the corn pollen used in this study.

Mean values of K_P from all of the releases on the Bere Stream and Frome Vauchurch were 0.016 ± 0.004 (SE) and 0.036 ± 0.013 (SE) m^{-1} respectively. The releases on the River Frome had conspicuously greater variation in K_P values compared to the releases on the Bere Stream. The mean K_P values within this study appeared to be similar with those from experimental releases within lowland vegetated streams by Warren *et al*. (2009) (0.015 ± 0.002 (SE) m^{-1}) and Koetsier and McArthur (0.022 ± 0.003 (SE) m^{-1}). K_P values for releases of UFPOM and VFPOM within unvegetated lowland streams by Hunken and Mutz (2007) were also comparable to the K_P values produced within this study (0.015 ± 0.024 (SE) m^{-1}). Additionally, the mean values of K_P from Frome Vauchurch were similar to those of the experimental releases by Minshall *et al*. (2000) (0.036 [1] ± 0.023 (SE) m^{-}) who performed experimental releases within unvegetated mountain streams with considerably greater slope gradients and lower discharges in comparison to both sites in this study.

This study was not able to determine the underlying factors or parameters influencing changes in V_{dep} values of the released corn pollen particles. Values of V_{dep} did not correlate with values of total macrophyte cover or *Ranunculus* cover. This suggests that seasonal changes in the values of V_{dep} for fine sediment particles were independent of total macrophyte cover and *Ranunculus* cover. However, it was observed that the greatest values of V_{dep} at both sites coincided with the greatest values of total macrophyte cover and low values of discharge in May 2009 and July 2009.

Mean V_{dep} values within Frome Vauchurch were greater than those of the Bere Stream at 5.80 ± 8.93 (SE) and 2.01 ± 1.47 (SE) mm s^{-1} correspondingly. These were considerably greater in comparison to the previous study on a vegetated stream by Warren *et al*. (2009) (1.27 ± 0.08 (SE) mm s^{-1}) and considerably greater than experimental releases from studies on unvegetated mountain streams (Georgian *et al*., 2003; Minshall *et al*., 2000; Thomas *et al*., 2001; Webster *et al*., 1999). But releases in this present study took place throughout two annual cycles on both stream sites. Whilst releases presented in previous studies compared streams over two seasons or less or in the same streams in periods of high and low discharge.

There are a number of other possibilities as to why changes in S_P, T and V_{dep} values were observed but they did not correspond with variations in seasonally changing macrophyte cover. The changing reconfiguration of macrophytes due to drag forces around their patches (Green, 2005a; O'Hare *et al*., 2007a; Sand-Jensen, 2003; Sand-Jensen and Pedersen, 1999; Statzner *et al*., 2006) may have had a potential influence due to the increased localised turbulence and plant monami (Ackerman, 1998; Nepf and Ghisalberti, 2008; Nepf and Vivoni, 2000; Okamoto and Nezu, 2009). Additionally, the presence of macrophytes may have affected the transient storage zone and transient storage zone exchange within the channel (Paul and Hall, 2002; Wagner and Harvey, 1997). The transient storage zone has been shown previously to be highly correlated with S_P and V_{dep} values of FPOM particles within unvegetated mountain streams (Minshall *et al*., 2000) and lowland streams (Hunken and Mutz, 2007). Difficulties remain in providing a representative estimate of the transient storage zone and transient storage zone exchange within vegetated streams.

A further factor that was not measured during this study, but would improve future research, was the extent to which gravels were in-filled with sand or colmated (Schälchli, 1992). The study by Warren *et al*. (2009) demonstrated that the in-filling of gravel with sand-sized particles in a flume led to significant decreases in S_P as well as increasing values of K_P and $V_{dep.}$ In this study, colmation of bare gravels between plant patches was not observed but rather confined to the areas of fine sediment accumulation within stands of vegetation.

5.2.2 The influence of channel porosity on fine sediment transport within vegetated lowland streams

The findings of this study suggest that the null hypothesis of seasonally changing values of channel porosity not being influenced by corresponding changes in total macrophyte cover is rejected, and the alternative hypothesis is accepted for both sites.

Datasets from the Bere Stream indicated that increases in channel porosity were primarily correlated with changes in total macrophyte cover and absolute volume as well as discharge. Seasonal changes in the cover and absolute volume of *Nasturtium* were suggested to have the greatest influence on channel porosity, with increasing cover and volume of *Nasturtium* being the most associated with decreases in channel porosity. This implied that the increased seasonal growth of *Nasturtium* in addition to corresponding decreases in discharge were the main dependant factors involved with decreasing channel porosity on the Bere Stream at Snatford Bridge, rather than corresponding values of area cover and absolute volume for *Ranunculus*. It has been demonstrated in this study and in a previous work by Wharton *et al*., (2006) that *Nasturtium* encroaches into the centre of the channel from the margins during low discharges and grows over emergent *Ranunculus* patches in the mid-channel at the Snatford Bridge site. This growth pattern is the most likely contributory factor that leads to decreasing channel porosity within the reach. The results of this study suggest that future management strategies on the Snatford Bridge site could include a greater emphasis of managing peak *Nasturtium* cover and volume by strategic removal of patches to increase flow conveyance through sections of the reach, this may consequently improve channel porosity.

Channel porosity on the River Frome at Frome Vauchurch was also greatly correalted with changes in total macrophyte cover. On the Frome Vauchurch site decreases in channel porosity were highly correlated with increases in the area cover and absolute volume of *Ranunculus* patches. Additionally, increases in mean channel velocity and discharge were well correlated with increases in channel porosity. The results of this study at Frome Vauchurch suggest that limited removal of *Ranunculus* patches at peak total vegetation cover could be considered to increase conveyance of high velocity flow through vegetation leading to increased channel porosity.

Values of channel porosity were not strongly correlated with corn pollen transport and deposition parameters from the seasonal reach-scale releases at either Bere Stream or Frome Vauchurch. On this basis the second null hypothesis can be accepted. This indicates that seasonal values of channel porosity cannot be used to directly compare or estimate corresponding fine sediment transport or retention within vegetated reaches. This implies that channel porosity or the three dimensional shape of unvegetated three water within vegetated reaches does not appear to be a major determinant of fine sediment transport. Channel porosity may yet be a contributory parameter that influences or impacts fine sediment transport and retention when it is combined with another parameter, but this was not demonstrated by the results of this study.

Currently there is no agreed standard method for assessing the impact of changing in-channel macrophyte growth on the transient storage zone and transient storage exchange within lowland rivers and streams. Values of channel porosity were intended to provide a rudimentary three dimensional estimate of the impact that macrophytes have upon water flowing within vegetated reaches and associated fine sediment transport and retention estimates; these are akin but less detailed than the Conveyance Estimation System developed by HR Wallingford (HR Wallingford LTD, 2010).

CHAPTER 6

Temporal and spatial changes in fine sediment deposition and particle characteristics within *Ranunculus* patches

6.0 Introduction

This chapter reports the results (section 6.1) and discussion (section 6.2) of a plant-scale investigation to examine the temporal and spatial changes in fine sediment deposition and sediment particle characteristics within *R. penicillatus subsp. pseudofluitans* (hereafter *Ranunculus*) patches between July 2008 and July 2009. Three *Ranunculus* plants were examined at both study sites during the observation period. The deposition and storage of fine sediment are examined in relation to corresponding seasonal changes of *Ranunculus* patch area and volume. Following this is a comparison of the differences in fine sediment particle characteristics between *Ranunculus* patches. An investigation into the spatial and temporal patterns of fine sediment particle characteristics between the five zones identified within *Ranunculus* patches was also conducted.

6.1 Results

6.1.1 Seasonal changes of fine sediment volume and deposition within plant patches on the Bere Stream between July 2008 and July 2009

6.1.1.1 Temporal changes in plant area and shape

There was a clear seasonal pattern of growth within the Bere Stream (Figure 6.1). Mean total plant area increased from November 2008 to March 2009 (2.60 m^2) which was the peak in areal cover. Subsequently after, the mean total plant area of the three *Ranunculus* plants decreased to 0.57 m^2 in July 2009. The plan view diagrams (Figure 6.2) of the plants made from measurements taken during the survey confirmed that plants appeared to reach maximum growth around March 2009 or May 2009, and subsequently declined through to July 2009.

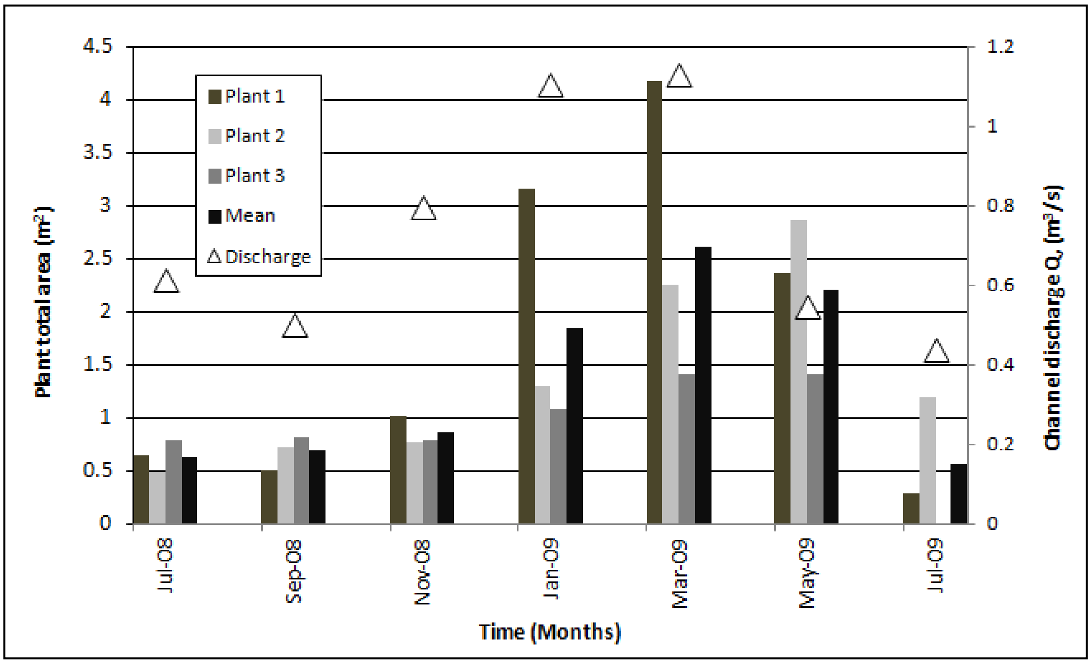


Figure 6.1 – Bimonthly changes in the total plant area (m^2) of all three *Ranunculus* study patches in addition to values of channel discharge (m^3 s^{-1}) on the Bere Stream at Snatford Bridge between July 2008 and July 2009.

Each plant had an individual pattern of seasonal growth. Plant one was the largest of the three stands throughout the survey period, and was the first to reach maximum growth in March 2009 (4.17 m^2). Plant two obtained maximum growth in May 2009 (2.86 m^2) before declining in July 2009. Plant three was the smallest of the three *Ranunculus* stands included in the survey. Maximum growth was acquired in March 2009 1.41 m^2 and persisted with the same areal cover until May 2009. Plant three was removed from the reach between the May 2009 and July 2009 surveys, with the presumption it had been physically removed by higher flow.

The plant rooted area is the most upstream section of *Ranunculus* plants and provides anchorage against the stream flow. The rooted area of the three plants was only measured from September 2008 to July 2009 (Figure 6.3), and no rooted area was recorded for plant three in July 2009 due to complete plant loss. Mean plant rooted area reached its peak at 0.98 m^2 in March 2009, but this was very close to the mean value in January 2009 of 0.96 m^2. The rooted area of plant one was initially the smallest, starting at 0.37 m^2 in September 2008, it subsequently peaked at 1.61 m^2 in January 2009 before receding to just 0.10 m^2 in July 2009. Plant two peaked at 1.30 m^2 in March 2009 and subsequently decreased to 1.04 m^2 in May and July 2009. The area of the rooted zone in plant three was initially the greatest of all three plants in September 2008 at 0.75 m^2.

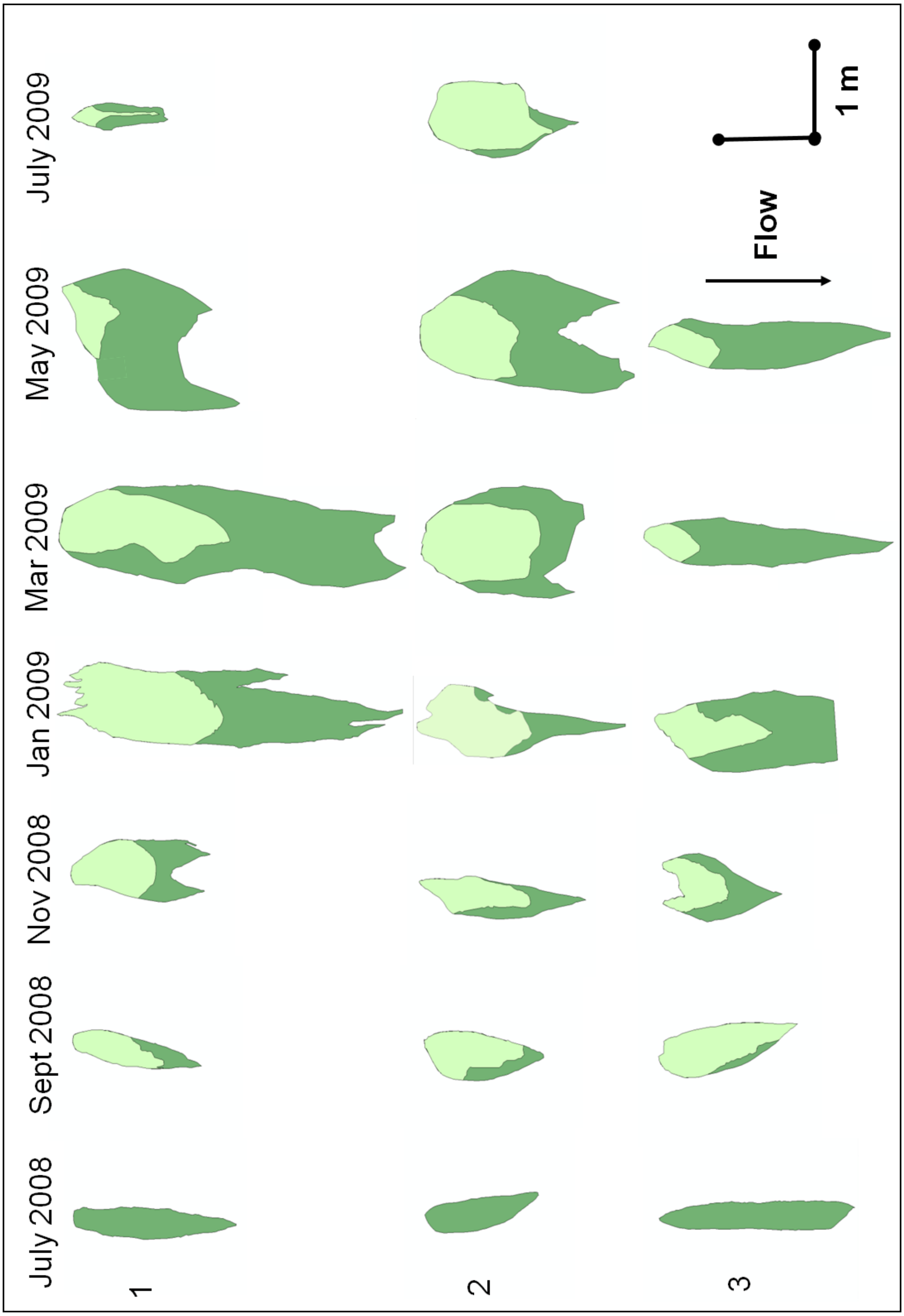


Figure 6.2– Seasonal changes in total plant area and rooted area of the three *Ranunculus* study patches on the Bere Stream at Snatford Bridge between July 2008 and July 2009. The light green zones within each plant designate the rooted section. The rooted area within all the three plants was not recorded in the July 2008 survey.

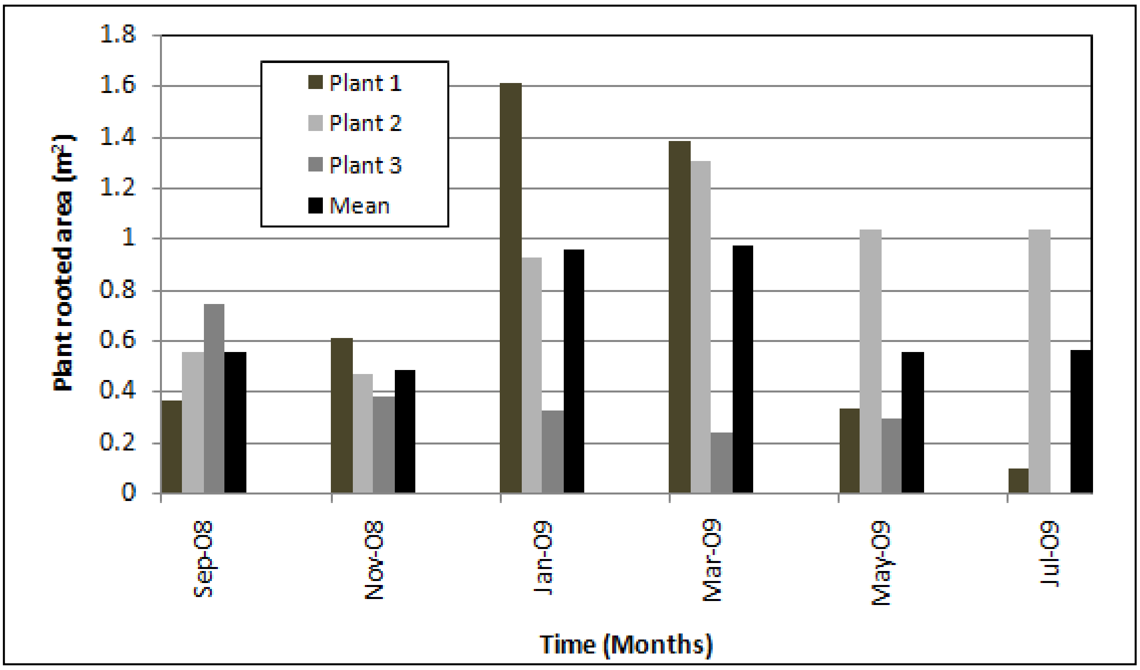


Figure 6.3 – The bi-monthly changes in the area cover of the rooted section (m^2) of all three *Ranunculus* study patches on the Bere Stream at Snatford Bridge between July 2008 and July 2009.

However, the rooted area appeared to gradually decline over the survey period with the lowest area being recorded in March 2009 at 0.24 m^2. The gradual decline in area may have been the reason for the eventual loss of the entire plant which occurred before the July 2009 survey.

The results of the calculated coefficients of determination for the scatterplot in Figure 6.4 revealed that there was a very significant relationship ($R^2 = 0.70$) between the rooted area of plants and the total area of plants within Bere Stream. Plant 1 had the greatest relationship between the total plant area and the rooted area at ($R^2 = 0.70$), followed by plant 2 ($R^2 = 0.57$) and plant 3 ($R^2 = 0.51$).

6.1.1.2 Temporal changes in composite plant volume

Values of plant volume that were calculated from field measurements were termed 'composite plant volume' because the estimated value contained both plant material and interstitial water between the plant fronds. Composite plant volume was calculated from survey measurements using a local polynomial interpolation within ArcGIS. The changes in composite plant volume within the plants surveyed on the Bere Stream appeared to be seasonal and closely followed that of the plant areal cover described above (Figure 6.5).

The mean composite plant volume reached its maximum value of 0.38 m^3 in March 2009, which coincided with the peak in mean area cover of the total plant area and the rooted sections. The volume of plant one started at 0.05 m^3 in July 2009 and reached its maximum value of 0.61 m^3 in March 2009, before decreasing in July 2009 to 0.02 m^3. The composite volume of plant two also peaked in March 2008 but at a lower value of 0.34 m^3, the subsequent decrease in composite volume after March 2009 was much less compared to the other two sample plants resulting in an ending volume of 0.13 m^3. The composite plant volume of the third plant initially increased in September 2008 before decreasing in November 2008 and reaching its peak in March 2009 at 0.18 m^3.

A scatterplot of the total plant area and the composite plant volume revealed that there was a significant positive linear relationship (R^2 = 0.93) between the two factors (Figure 6.6). The scatterplot between total plant area and composite plant volume also revealed highly significantly associations in plant one possessed (R^2 = 0.94), followed by plant two (R^2 = 0.93) and then plant three (R^2 = 0.64).

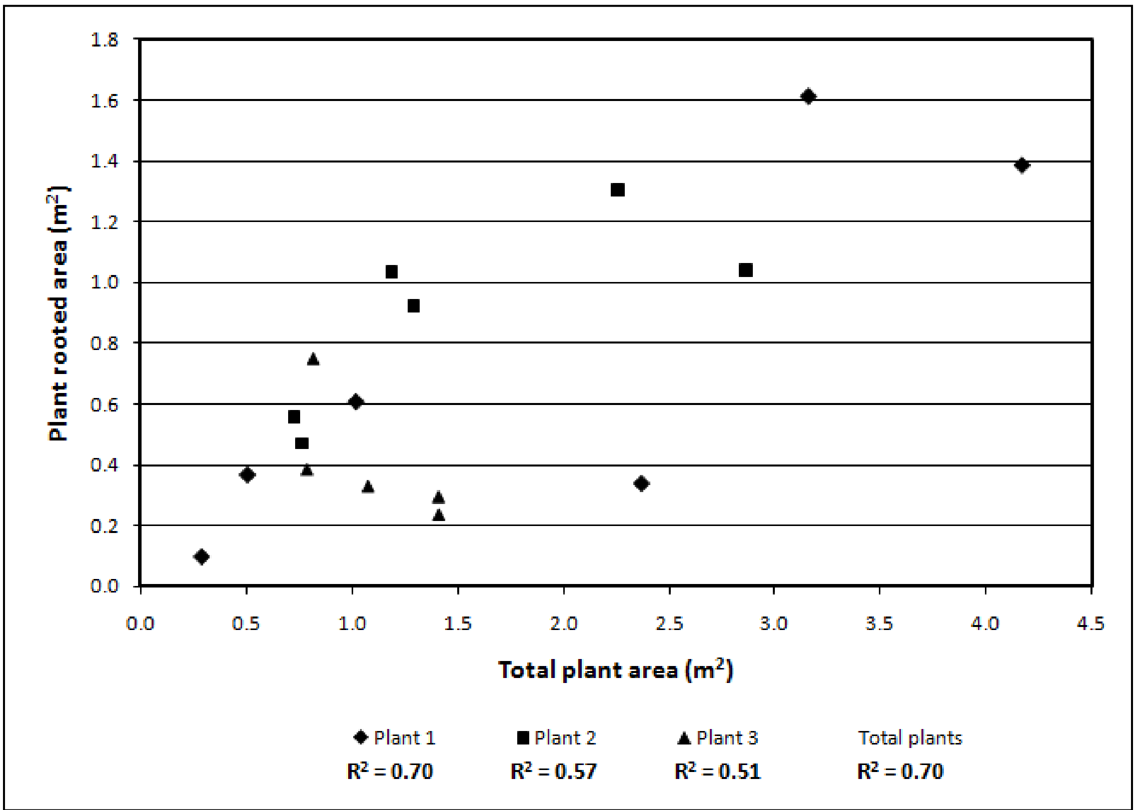


Figure 6.4 – A scatterplot of the total plant area (m^2) and rooted area (m^2) for three *Ranunculus* patches on the Bere Stream at Snatford Bridge. 'Total plants' represents the combined datapoints from all three plants. The calculated coefficients of determination (R^2) are shown for all three plants and for all datapoints combined**.** The July 2008 data were not included due to the absence of rooted area data from the July 2008 sample month.

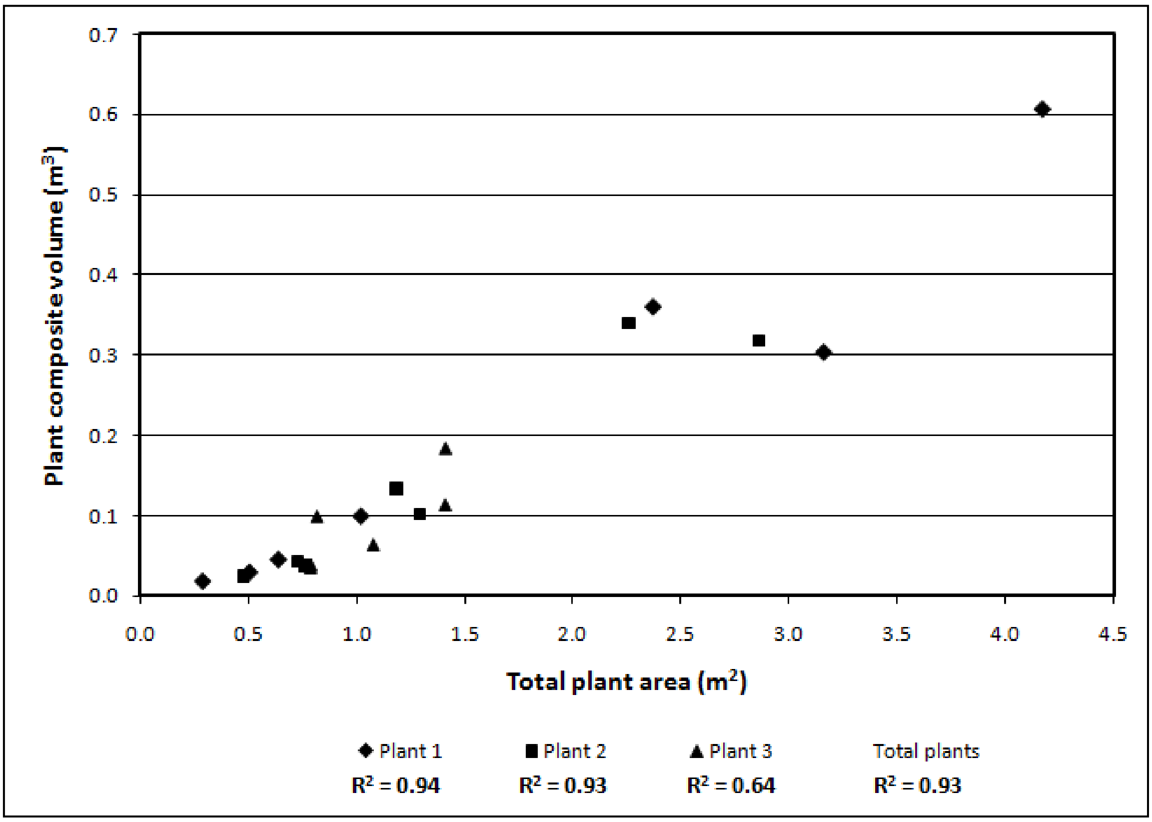


Figure 6.5- A scatterplot illustrating the relationship between values of total plant area (m^2) and composite plant volume (m^3) from the three *Ranunculus* patches on the Bere Stream at Snatford Bridge. 'Total plants' represents the combined datapoints from all three plants. The calculated coefficients of determination (R^2) are shown for all three plants and all of the datapoints combined**.** The July 2008 data were not included due to the absence of rooted area data from the July 2008 sample month.

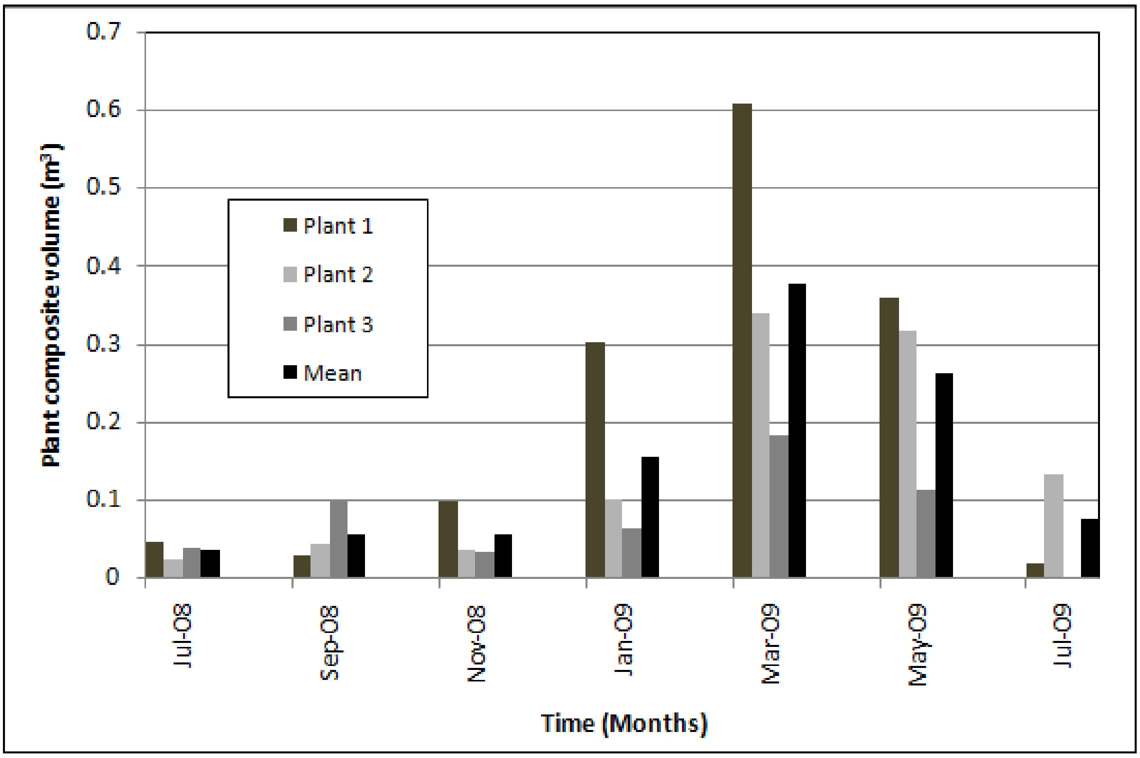


Figure 6.6 – The seasonal changes in composite plant volume (m^3) (vegetation and water) within the three *Ranunculus* study patches on the Bere Stream at Snatford Bridge between July 2008 and July 2009.

6.1.1.3 Spatial and temporal changes in fine sediment deposition and distribution within *Ranunculus* plants

A central part of this study was to investigate the spatial-temporal changes of fine sediment deposition and characteristics within individual *Ranunculus* patches in relation to their corresponding changes in physical morphology. The distribution and depth of sediment within the six *Ranunculus* stands was recorded during the one year survey from July 2008 to July 2009 (Figure 6.7).

The series of diagrams in Figure 6.7 suggest that the majority of the deposited fine sediment was accumulating within the rooted sections of the three *Ranunculus* plants on the Bere Stream throughout the whole year. It appeared that fine sediment was initially deposited within the rooted area of all three plants, and following this it expanded to the rest of the plant throughout the survey period.

In July 2008 fine sediment was concentrated in the middle of plant one and three. The sediment in plant two was skewed more towards the right side of the plant. In September 2008 fine sediment was distributed in a single small patch that was well within the rooted section of each plant. In November 2008 fine sediment had started to accumulate outside of the rooted zone within all three plants, and this persisted through to the March 2009 survey. In plants one and two there was practically no fine sediment present within the most upstream part of the rooted area in March 2009. By May 2009 the fine sediment had retreated back into the rooted zones of plant two and three, sediment in both plants were still concentrated in one patch. In plant one the fine sediment had accumulated into several small distinct but interconnecting patches. Within the July 2009 survey the fine sediment underneath plant one and two was concentrated well within the rooted zone.

Fine sediment volume was estimated underneath each *Ranunculus* plant in every survey, a mean fine sediment volume value was produced for each month surveyed (Figure 6.8). The mean volume of fine sediment appeared to have a seasonal pattern resembling a Gaussian distribution which appeared to correspond with the mean area cover for each month (see section 6.1.1.1). Mean fine sediment volume peaked in March 2009 at 0.13 m^3.

Plant one accumulated the greatest volume of sediment over the one year period, the peak in sediment volume underneath plant one occurred in January 2009 at 0.17 m^3.

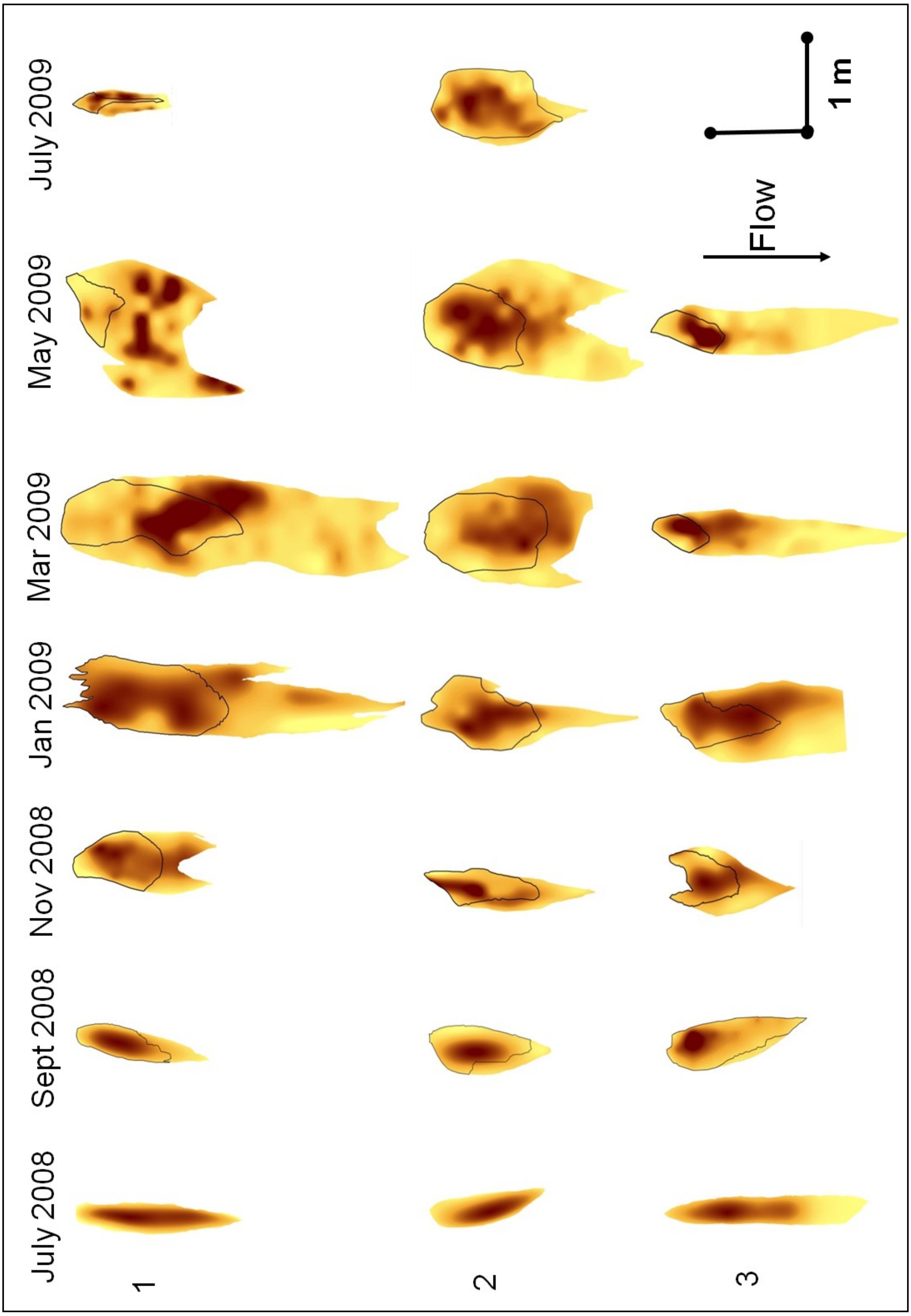


Figure 6.7 - Seasonal changes in the spatial distribution of fine sediment and the depth of deposits within the three *Ranunculus* study patches on the Bere Stream at Snatford Bridge between July 2008 and July 2009. The darker areas indicate high sediment accumulation (depth), the rooted section of the plant is demarcated by a black line.

Plant two accumulated the second greatest fine sediment volume, with the peak in sediment volume occurring in March 2009 at 0.16 m^3. Plant three accumulated the least fine sediment volume over the one year period, and the maximum sediment volume was considerably less compared to the other two plants at 0.07 m^3.

Calculated coefficients of determination in the scatterplot in Figure 6.9 revealed that the total area cover values of the *Ranunculus* plants had a significant relationship with the corresponding fine sediment volume that accumulated underneath them (R^2 = 0.82). The relationship suggests the volume of fine sediment increased when increasing plant area cover. The resulting R^2 values between total area and fine sediment volume in plants one and two were highly significant, at $R^2 = 0.86$ and $R^2 = 0.92$ correspondingly. However, the data suggested that the relationship was not as significant within plant 3 ($R^2 = 0.39$).

A further scatterplot between all of the values for plant rooted area and fine sediment volume within the rooted area revealed a significant result of $R^2 = 0.86$ (Figure 6.10). The R^2 values for all three plants were also highly significant. This suggested that increases in the rooted area of all three plants were linked to corresponding increases in fine sediment volume within the rooted section of plants.

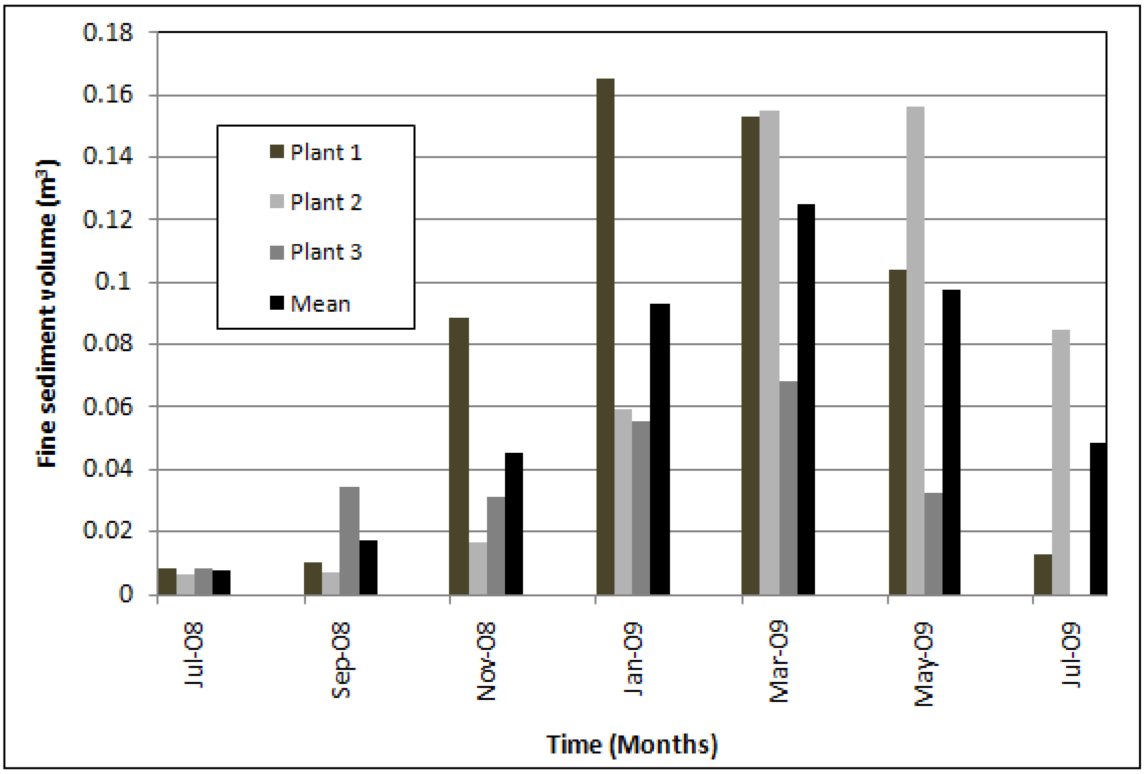


Figure 6.8 - The seasonal changes of fine sediment volume (m^3) within the three *Ranunculus* study patches on the Bere Stream at Snatford Bridge between July 2008 and July 2009.

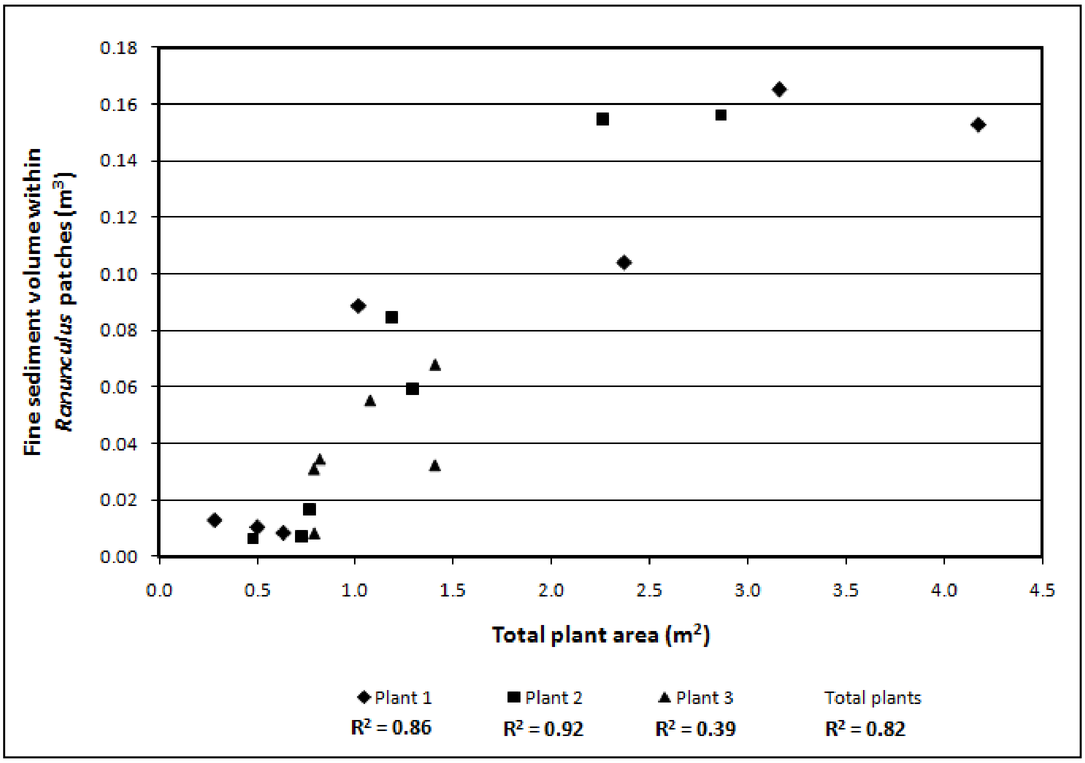


Figure 6.9 – A scatterplot of the relationship between total plant area (m^2) and fine sediment volume (m^3) within the three *Ranunculus* study patches on the Bere Stream at Snatford Bridge. 'Total plants' represents the combined datapoints from all three plants. The calculated coefficients of determination (R^2) are shown for all three plants and all of the datapoints combined**.**

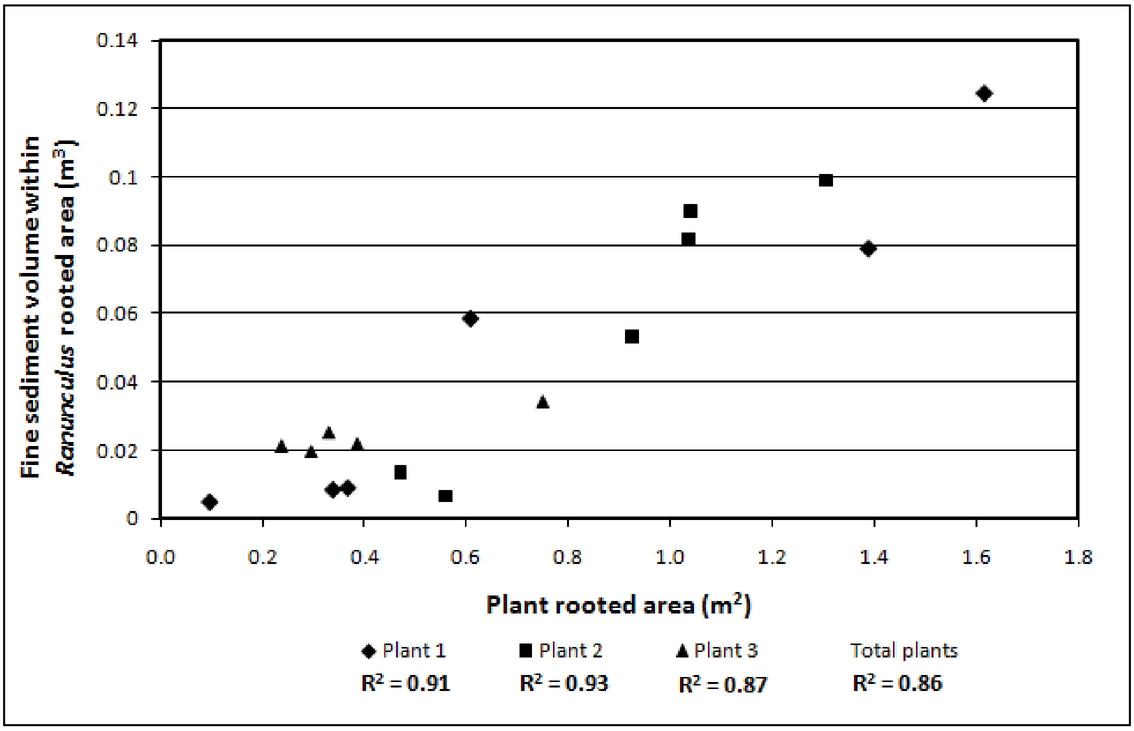


Figure 6.10 - A scatterplot of the relationship between the plant rooted area (m^2) and fine sediment volume (m^3) within the rooted area of the three *Ranunculus* study patches on the Bere Stream at Snatford Bridge. 'Total plants' represents the combined datapoints from all three plants. The calculated coefficients of determination (R^2) are shown for all three plants and all datapoints.

A further scatterplot between total plant composite volume and total fine sediment volume also revealed a significant relationship of $R^2 = 0.76$ (Figure 6.11). The R^2 value of plant three was not as significant ($R^2 = 0.49$) as the other two plants. Despite this, these results suggest that increases in plant composite volume were associated with increases in the volume of surficial fine sediment deposited within plant patches.

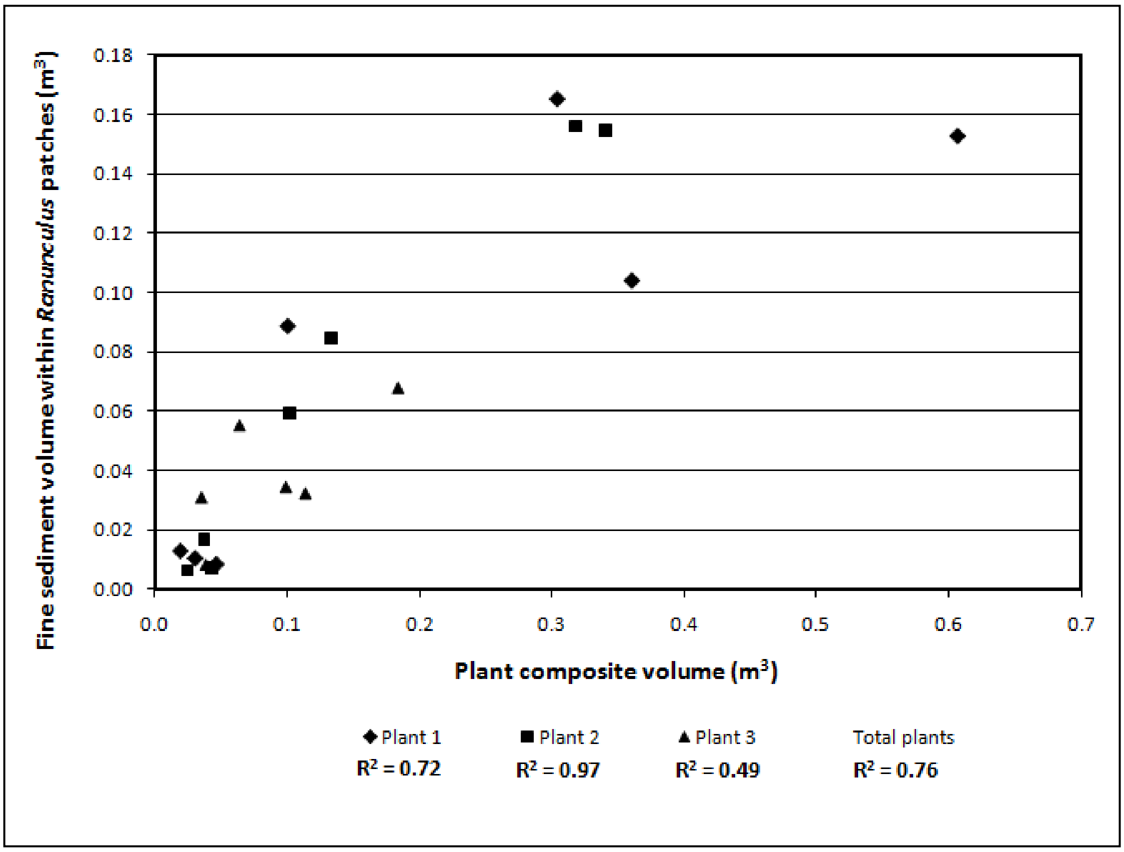


Figure 6.11 – A scatterplot of the relationship between the plant composite volume (m^3) and fine sediment volume (m^3) within the three *Ranunculus* study patches on the Bere Stream at Snatford Bridge. ''Total plants' represents the combined datapoints from all three plants. The calculated coefficients of determination (R^2) are shown for all three plants and all of the datapoints combined. The July 2008 data were not included due to the absence of rooted area data from the July 2008 sample month.

6.1.2 Seasonal changes of fine sediment volume and deposition within plant patches on the River Frome between July 2008 and July 2009

6.1.2.1 Temporal changes in plant area and shape

There appeared to be a weaker seasonal trend in the growth and recession of the measured plants within Frome Vauchurch (Figure 6.12) in comparison with the plants on the Bere Stream, which exhibited noticeably greater seasonal growth responses. The mean total area of the plants varied only slightly within the one year survey period. A small peak in mean total area occurred in May 2009 at 2.05 m^2. The month with the least mean total area was January 2009 at 1.32 m^2. The plan view diagrams of the *Ranunculus* plants throughout the survey period (Figure 6.13) confirm that there was little seasonal change in their growth and recession. The three plants were only truly comparable in size during the July 2008 survey month.

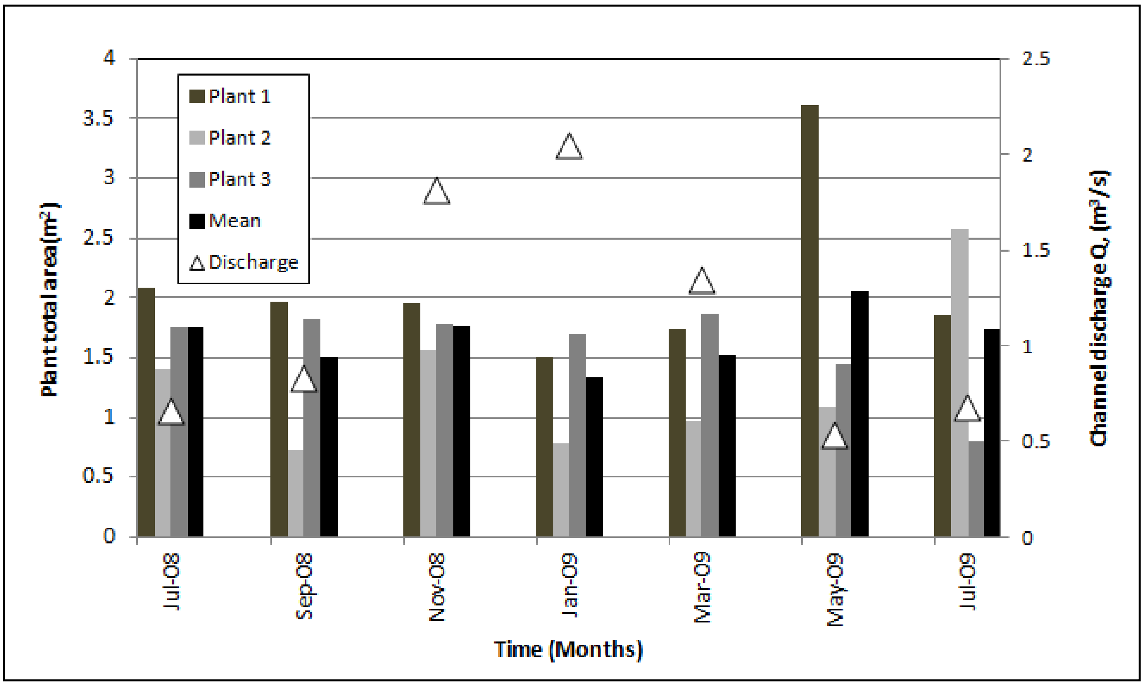


Figure 6.12 - Bimonthly changes in the total plant area (m^2) of all three *Ranunculus* study patches in addition to values of channel discharge (m^3 s^{-1}) on the River Frome at Frome Vauchurch between July 2008 and July 2009.

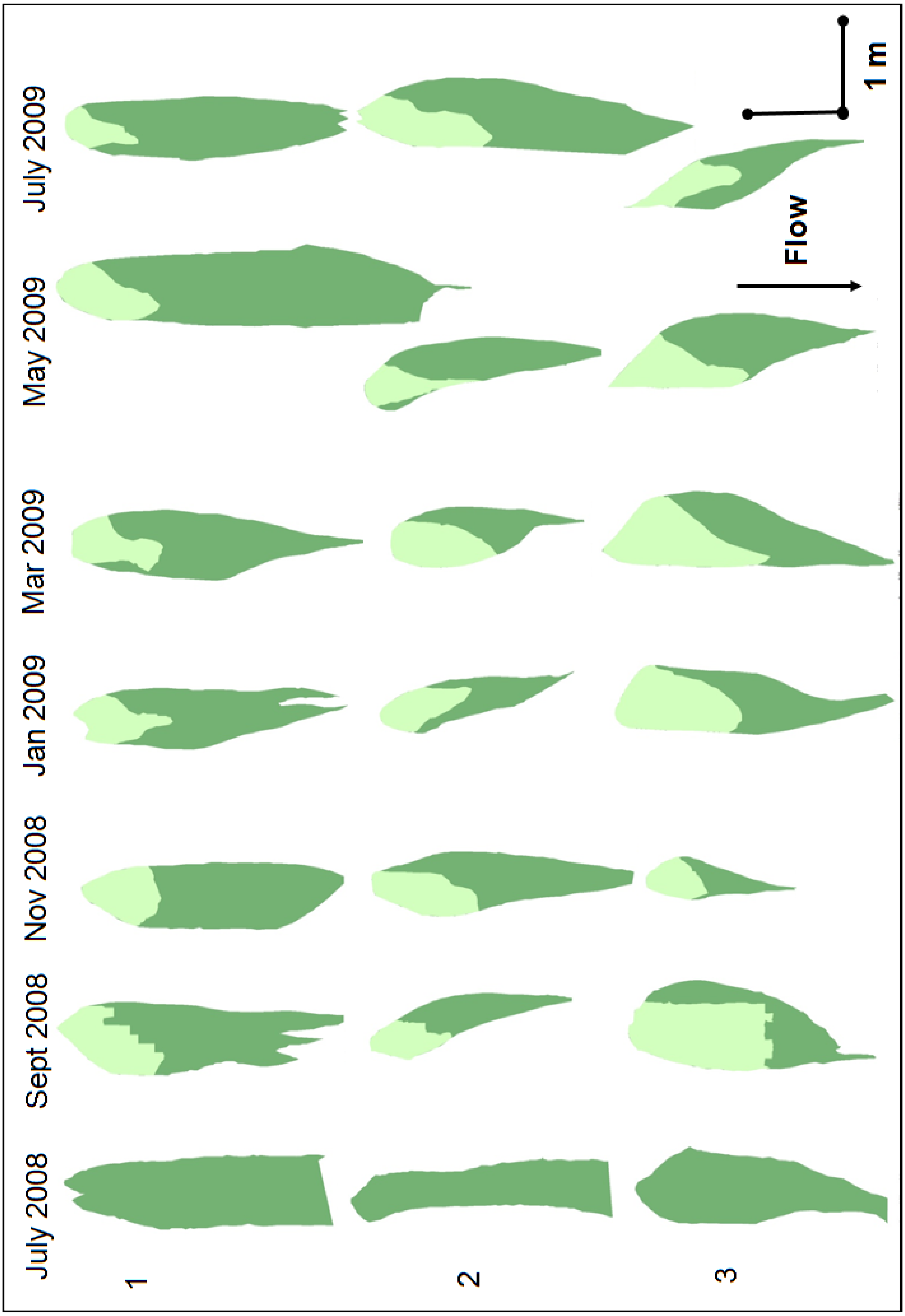


Figure 6.13- Seasonal changes in total plant area and rooted area of the three *Ranunculus* study patches on the River Frome at Frome Vauchurch between July 2008 and July 2009. The light green zones within each plant designate the rooted section.

Plant one was the largest of the three plants. It achieved maximum growth in May 2009 of 3.61 m^2, and had the lowest area cover in January 2009 of 1.51 m^2. Plant two was at its peak growth during July 2009 at 2.57 m^2, but had a subsequent increase in area cover during November 2008 to 1.57 m^2. Plant three was the smallest of all three plants in the survey. Peak growth of plant three occurred in March 2009 at 1.87 m^2, with an earlier increase in cover occurring in September 2008 (1.83 m^2).

The rooted area of the study plants was measured from September 2008 to July 2009 (Figure 6.14). The mean rooted area of the plants was at its peak in September 2008 at 0.63 m^2. From September 2008 the mean rooted area appeared to decrease overall during the period of the survey, with the exception of a small increase in March 2009 to 0.58 m^2. The rooted area of plant one started at 0.57 m^2 and subsequently decreased through to 0.35 m^2 in January 2009 before increasing to its peak area cover of 0.52 m^2 in May 2009. Plant two had the most variable rooted area over the measurement period and started in September 2008 with the smallest rooted area of all three plants at 0.25 m^2. The rooted area of plant two increased in November 2008 (0.50 m^2) only to

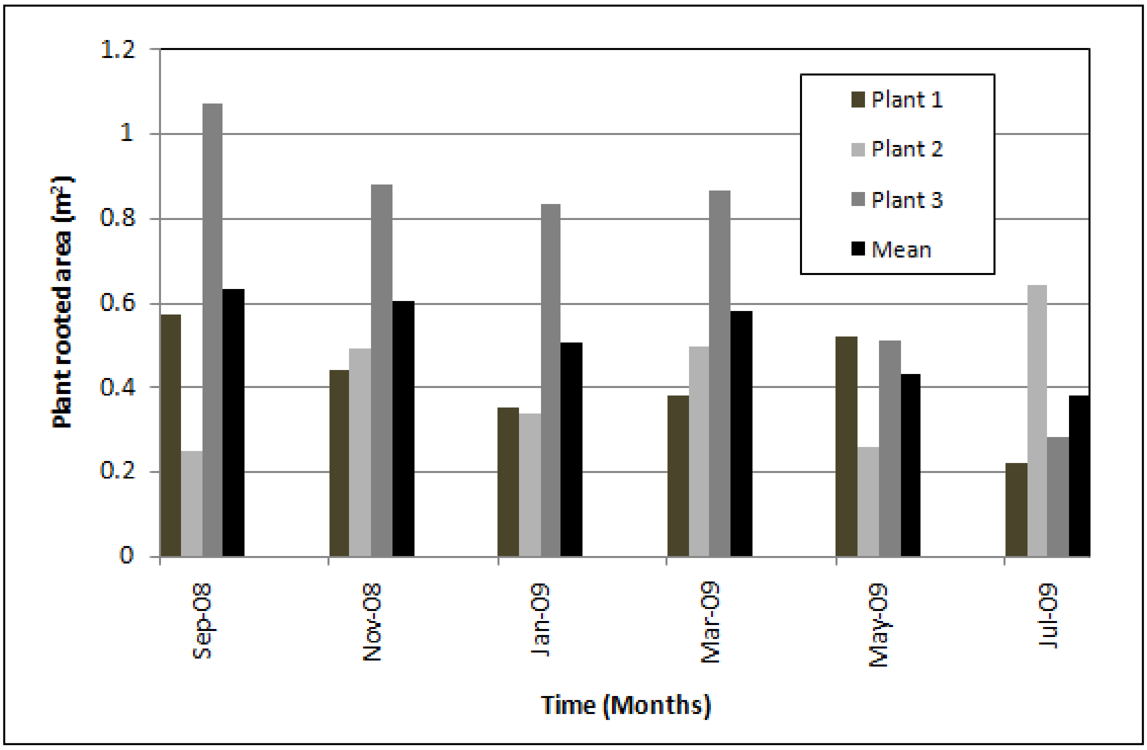


Figure 6.14 - The bimonthly changes in the areal cover of the rooted area (m^2) of all three *Ranunculus* study patches on the River Frome at Frome Vauchurch between September 2008 and July 2009.

decrease to 0.34 m^2 in January 2009. This was followed by an increase in rooted area to 0.50 m^2 in March 2009, and a subsequent decrease in May 2009 to 0.26 m^2. A further increase in rooted area to 0.64 m^2 occurred in July 2009, which was the peak in the rooted area of plant two. The rooted area of plant three was the greatest of the three surveyed plants in September 2008 at 1.07 m^2. The rooted area subsequently decreased to 0.83 m^2 in January 2009 before slightly enlarging in March 2009 to 0.87 m^2. From therein the rooted area of plant three then gradually declined to just 0.28 m^2 in July 2009.

The scatterplot in figure 6.15 indicated that there was a limited relationship ($R^2 = 0.13$) between the rooted area values and corresponding values of total area plant area. However, highly significant linear relationships were found between the rooted area and total area within the three individual *Ranunculus* plants. Plant 3 had the greatest relationship between the total plant area and the rooted area ($R^2 = 0.86$), followed by plant 2 ($R^2 = 0.68$) and plant 1 ($R^2 = 0.24$).

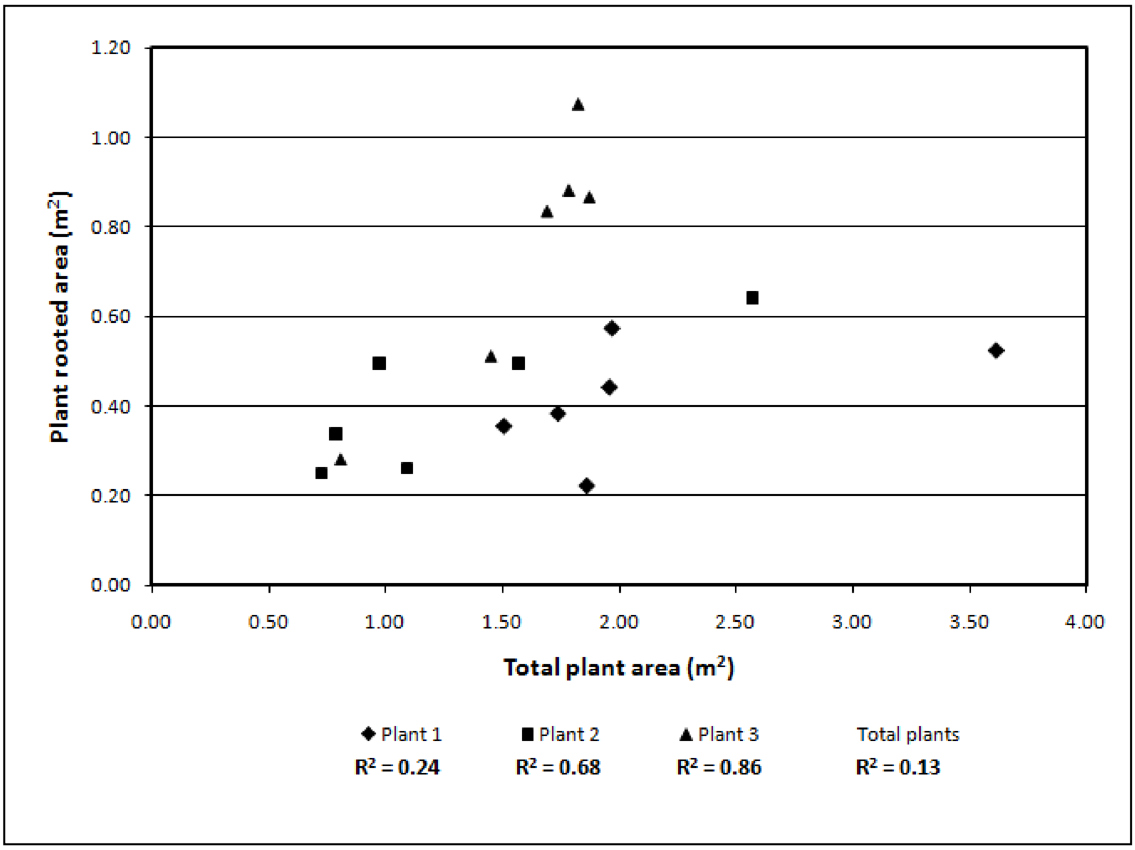


Figure 6.15- A scatterplot of the relationship between total plant area (m^2) and rooted area (m^2) within the three *Ranunculus* patches on the River Frome at Frome Vauchurch. 'Total plants' represents the combined data from all three plants. The July 2008 data were not included due to the absence of rooted area data from the July 2008 sample month. The calculated coefficients of determination (R^2) are shown for all three plants and all of the datapoints combined.

6.1.2.2 Temporal changes in composite plant volume

The composite plant volume was calculated from the field measurements of all three plants over the survey period from July 2008 to July 2009 (Figure 6.16). There was a seasonal change in the composite plant volume, and this corresponded with a change in total plant area within each plant during the measurement period.

The mean composite plant volume decreased gradually from 0.21 m^3 in July 2008 to 0.14 m^3 in January 2009. The composite plant volume subsequently increased to 0.24 m^3 in May 2009, which was the peak in composite plant volume during the survey period. This was significantly lower than that of the Bere Stream mean composite volume which peaked in March 2009 at 0.38 m^3. The peak of the mean composite plant volume coincided with the mean plant area, but not with the mean rooted plant area which had peaked in July 2008. The composite volume of plant one was 0.23 m^3 at the start of the survey in July 2008, this decreased gradually to just 0.12 m^3 in January 2009 before reaching a peak of 0.42 m^3 in May 2009. Plant one ended the survey in July 2009 with a composite plant volume of only 0.15 m^3. Plant two had the least composite plant volume at the start of the survey in July 2008 of 0.19 m^3. The composite volume decreased in September 2008 to 0.10 m^3 only to increase in November 2009 to 0.18 m^3.

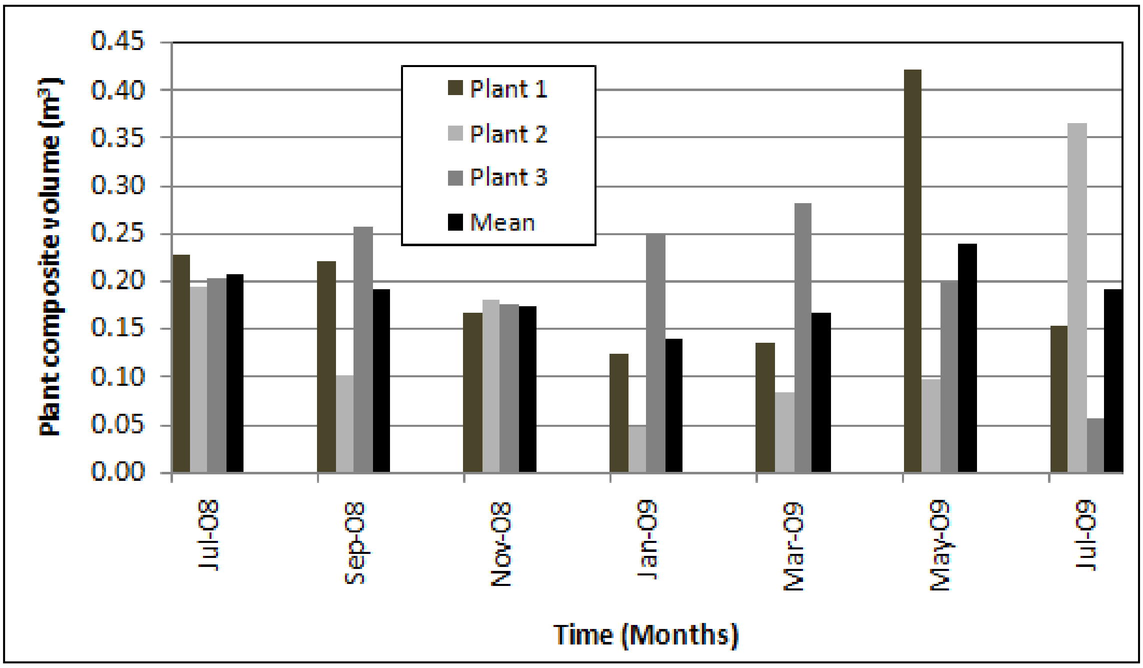


Figure 6.16 - The seasonal changes in composite plant volume (m^3) (vegetation and water) within the three *Ranunculus* study patches on the River Frome at Frome Vauchurch between July 2008 and July 2009.

The lowest composite plant volume measured in plant two was 0.05 m^3 during the January 2009 survey. From January 2009 the composite plant volume in plant two had steadily increased to the maximum value of 0.37 m^3 in July 2009. The composite plant volume of plant three was similar to the corresponding plant area measured within the same month. The volume increased from 0.20 m^3 in July 2008 to 0.26 m^3 in September 2008. The plant volume then decreased to its lowest value of 0.18 m^3 in November 2008, before slowly increasing to its maximum value of 0.28 m^3 in March 2009. Composite plant volume within plant three declined in May 2009 to 0.20 m^3, and experienced a further notable decrease to 0.06 m^3 in July 2009.

The scatterplot for total plant area and composite plant volume in figure 6.17 suggested there was a highly significant relationship (R^2 = 0.81) between the two factors. The linear relationship between total plant area and composite plant volume within plant one (R^2 = 0.96), plant two (R^2 = 0.95) and plant three (R^2 = 0.80) were very significant. Therefore, composite plant volume within individual stands tended to increase when total plant area increased.

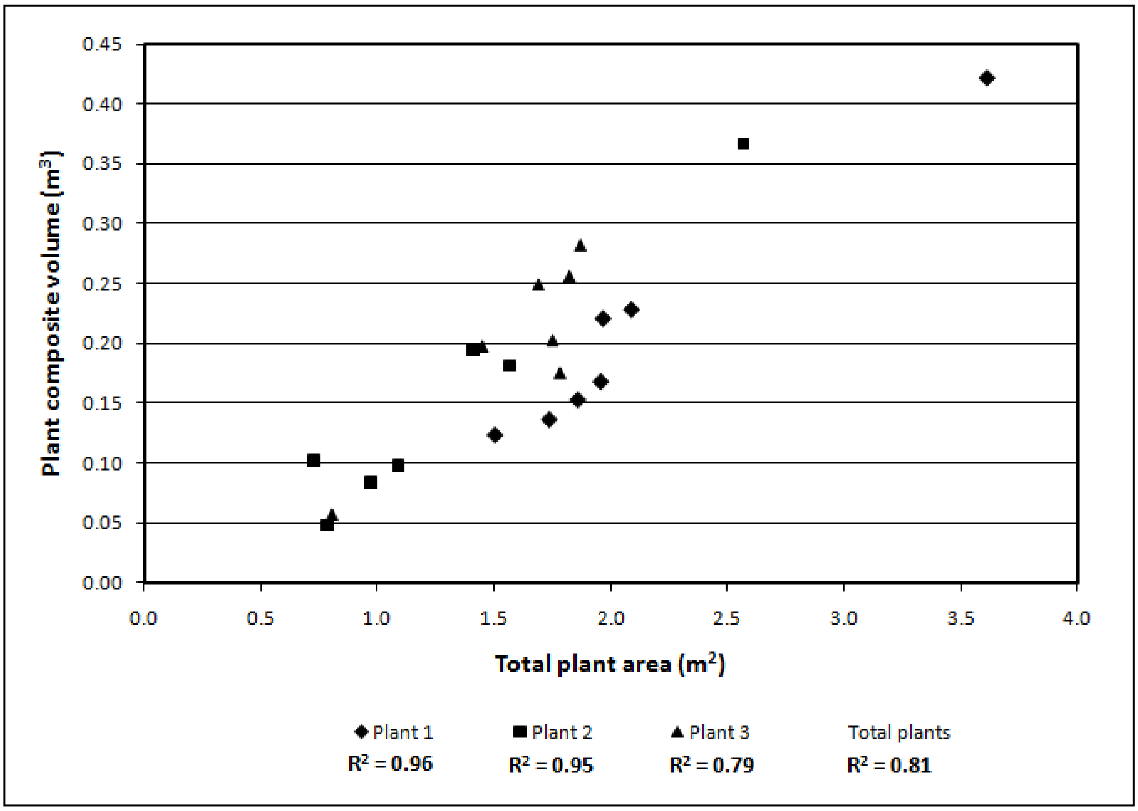


Figure 6.17- A scatterplot illustrating relationship between total plant area (m^2) and composite plant volume (m^3) within the three *Ranunculus* patches on the River Frome at Frome Vauchurch. 'Total plants' represents the combined data from all three plants. The calculated coefficients of determination (R^2) are shown for all three plants and all of the datapoints combined.

6.1.2.3 Spatial and temporal changes in fine sediment deposition and distribution within *Ranunculus* plants

The distribution and depth of deposited fine sediment within the *Ranunculus* study stands was recorded during the one year survey period (Figure 6.18). The sediment distribution appeared to be highly variable from plant to plant, and the size of the sediment patch was proportional to the size of the total area cover of the plant.

In July 2008 fine sediment was well distributed throughout the area covered by each plant, but there was a higher accumulation in the upper middle end of each plant. From September 2008 to March 2009 fine sediment was concentrated within a single discrete patch within all plants.

The sediment patch within plant one was found to be concentrated in one large patch that extended out of the rooted area between September 2008 and March 2009. The accumulated sediment maintained a roughly circular shape that was located within the top-middle section of the plant. The sediment patch constrained was within the rooted area during May 2009 and July 2009.

The sediment patch within plant two was only completely restricted to the rooted area during March 2009 and July 2009. During the other months fine sediment was distributed both inside and outside of the rooted area of plant two. During November 2008 the majority of the fine sediment patch was constricted within the rooted area, but there was a smaller sediment patch developing outside of the rooted area. In January 2009 the fine sediment patch outside of the rooted area was more prominent, and the patch that was in the rooted area appeared to be greatly reduced in area and sediment accumulation. During Mary 2009 three smaller patches of highly accumulated fine sediment had developed, two were within the rooted area and the other was in the unrooted trailing section. By July 2009 the rooted section had increased in area cover again, and the larger fine sediment patch was concentrated within the rooted zone. There was still a smaller patch of fine sediment within the rooted section of the plant.

Sediment in plant three was located within one discrete patch that was restricted to the rooted area between September 2008 and March 2009. The area cover of the sediment patch appeared to be proportional to the size of the rooted section. In May 2009 the sediment patch had started to migrate out of the rooted zone. In the final

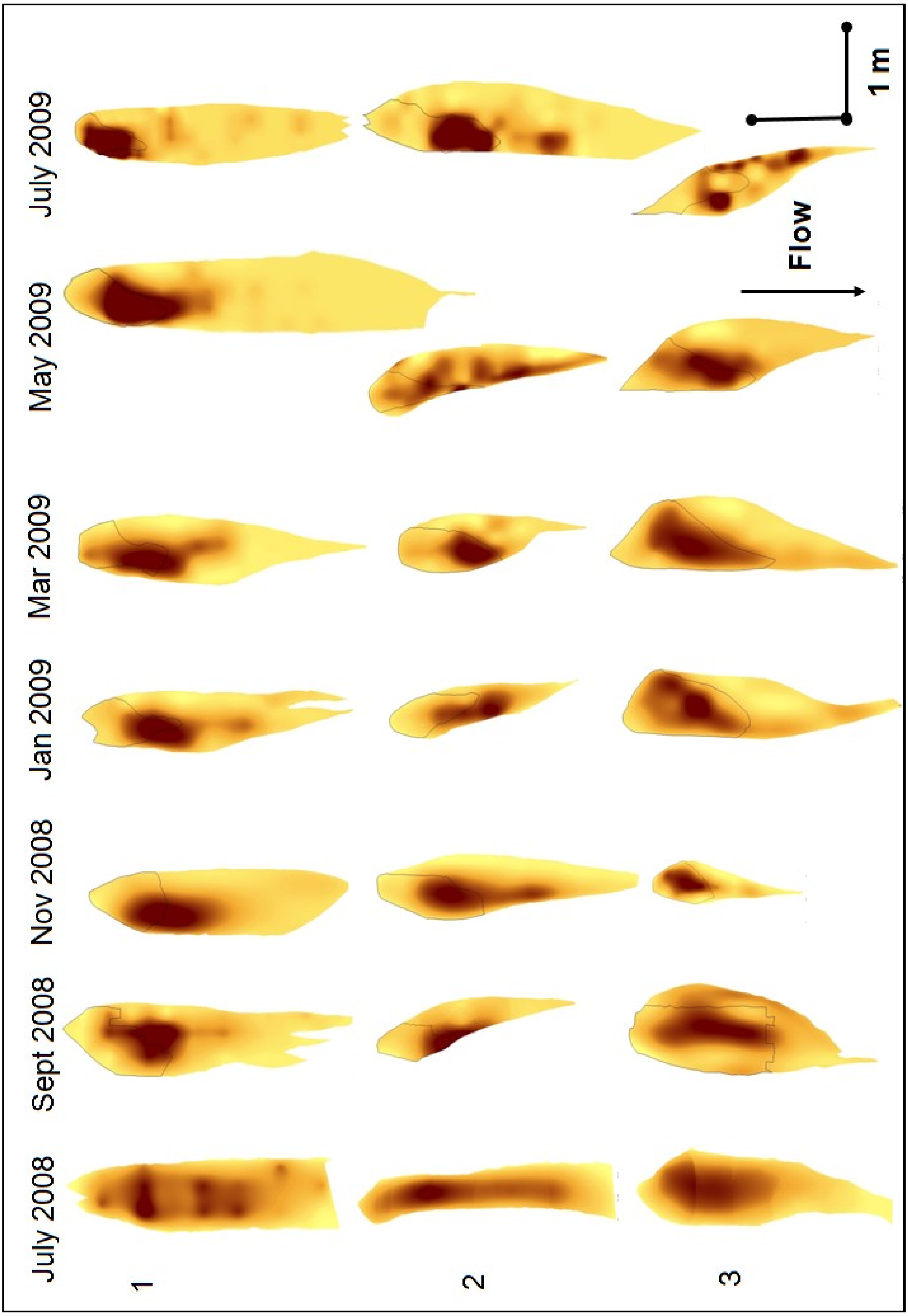


Figure 6.18 - Seasonal changes in the spatial distribution of fine sediment and the depth of deposits within the three *Ranunculus* study patches on the River Frome at Frome Vauchurch between July 2008 and July 2009. The darker areas indicate high sediment accumulation (depth), the rooted section of the plant is demarcated by a black line.

survey in July 2009 there were two larger patches fine sediment that were considerably smaller compared to the previous single patch. All of the patches were located outside of the rooted area of the plant, with one sediment patch located considerably downstream in the trailing section.

Patterns of fine sediment accumulation underneath the three *Ranunculus* plants appeared to be highly ephemeral throughout the survey period, and located in and outside of the rooted area of plants. The size, shape and depth of fine sediment accumulation appeared to be highly variable between the three plants.

An estimate of the fine sediment volume was calculated for each *Ranunculus* plant in every survey, a mean fine sediment volume value from all plants was produced for each survey month (Figure 6.19). There appeared to be a seasonal pattern to the mean volume of fine sediment. The peak of the mean fine sediment volume was in November 2008 at 0.06 m^3, this was considerably less than that of the Bere Stream (*c.f.* 0.13 m^3 in March 2009). July 2008 and July 2009 had considerably low mean fine sediment volumes at 0.04 m^3.

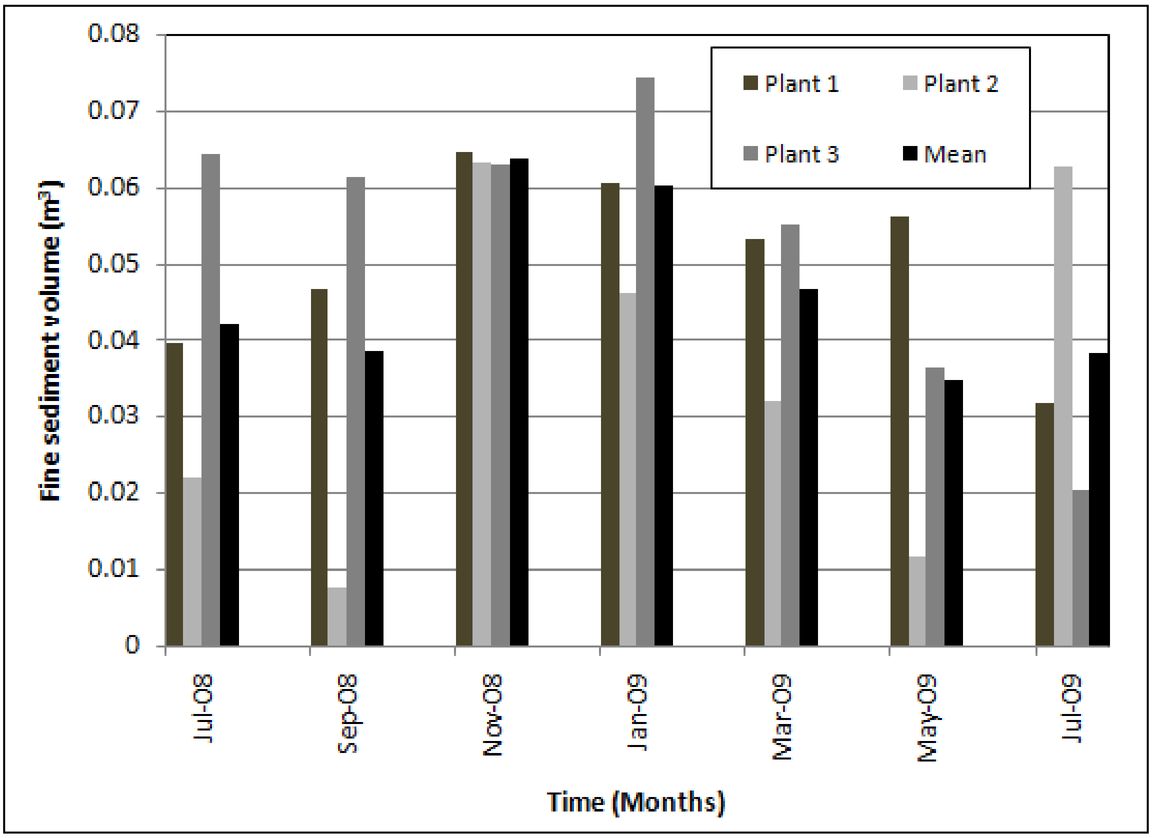


Figure 6.19 - The seasonal changes of fine sediment volume (m^3) within the three *Ranunculus* study patches on the River Frome at Frome Vauchurch between July 2008 and July 2009.

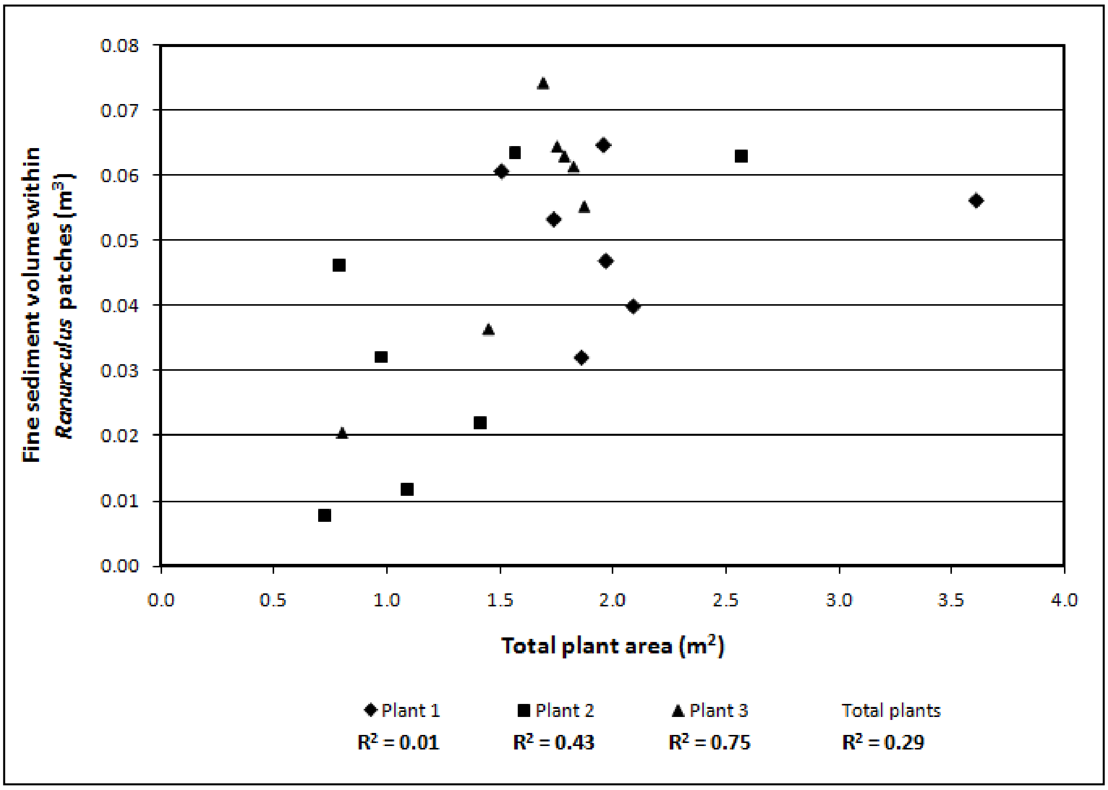


Figure 6.20 – A scatterplot of the relationship between total plant area (m^2) and fine sediment volume (m^3) within the three *Ranunculus* study patches on the River Frome at Frome Vauchurch. 'Total plants' represents the combined data from all three plants. The calculated coefficients of determination (R^2) are shown for all three plants and all of the datapoints combined.

Fine sediment volume was greatest in plant three in comparison to the other two plants. The peak in fine sediment volume in plant three occurred in January 2009 at 0.07 m^3. From January 2009 the sediment volume appeared to decrease exponentially, resulting in a considerably lower sediment volume of 0.02 m^3 in July 2009.

Plant one had the second greatest volume of fine sediment, with a peak of fine sediment volume at 0.06 m^3 in November 2009. Fine sediment volume increased from July 2008 to November 2008, and then slowly decreased through to March 2009 (0.05 m^3), before increasing slightly in May 2009 and subsequently decreasing in July 2009 to 0.03 m^3.

Plant two had the lowest accumulation of fine sediment volume, with a peak of 0.06 m^3 occurring in November 2008 and July 2009. From November 2008 fine sediment volume decreased exponentially to just 0.01 m^3 in May 2009. The smallest sediment volume underneath plant two was estimated as 0.007 m^3 in September 2008.

The scatterplot in figure 6.20 revealed there was a low significant association (R^2 = 0.29) between the total area cover of *Ranunculus* plants and the corresponding accumulated fine sediment volume. Plant one demonstrated the least

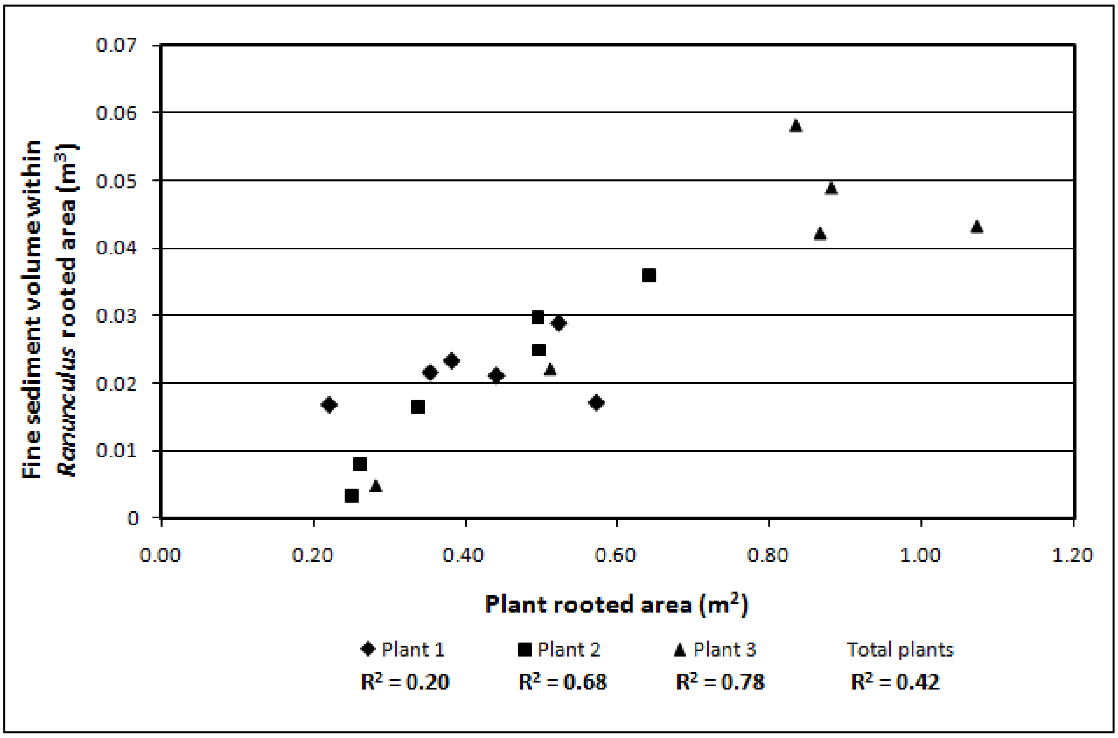


Figure 6.21 – A scatterplot illustrating the relationship between total plant area (m^2) and rooted area (m^2) from three *Ranunculus* patches on the River Frome at Frome Vauchurch. 'Total plants' represents the combined data from all three plants. The July 2008 data were not included due to the absence of rooted area data from the July 2008 sample month. The calculated coefficients of determination (R^2) are shown for all three plants and all of the datapoints combined.

significant relationship between the total area cover and total sediment volume (R^2 = 0.01), followed by plant two (R^2 = 0.43) and finally plant three (R^2 = 0.75) which had the most significant. This suggests that changes in the values of total area from individual *Ranunculus* plants are not always proportional values for total sediment volume.

The scatterplot in figure 6.21 revealed there was a non-significant relationship (R^2 = 0.42) between values rooted area and corresponding values for total fine sediment volume when the data from all three plants was added into the analysis. The analysis between the rooted area values and the total sediment volume values from the three plants revealed that plant one (R^2 = 0.20) had the least relationship, followed by plant two (R^2 = 0.68) and plant three (R^2 = 0.78) which demonstrated significant relationships between the two parameters. This result suggests that increases in values of rooted area do not always correspond with increases in total sediment volume within all *Ranunculus* patches on the site at Frome Vauchurch.

Figure 6.22 is a further scatterplot illustrating the relationship between values for plant rooted area and the fine sediment volume deposited beneath the plant rooted area from all three plants. The analysis revealed there was a limited association between the two parameters when datasets from all three plants were included (R^2 = 0.45). Further regressions were then performed on these parameters within the three individual plants. Plant two had the least significant relationship between the two parameters (R^2 = <0.01), followed by plant one (R^2 = 0.30) and plant three (R^2 = 0.90) which was highly significant. This set of results suggests that increasing values of plant rooted area do not always correspond with associated increases in sediment volume values within the rooted area of *Ranunculus* plants on the Frome Vauchurch site.

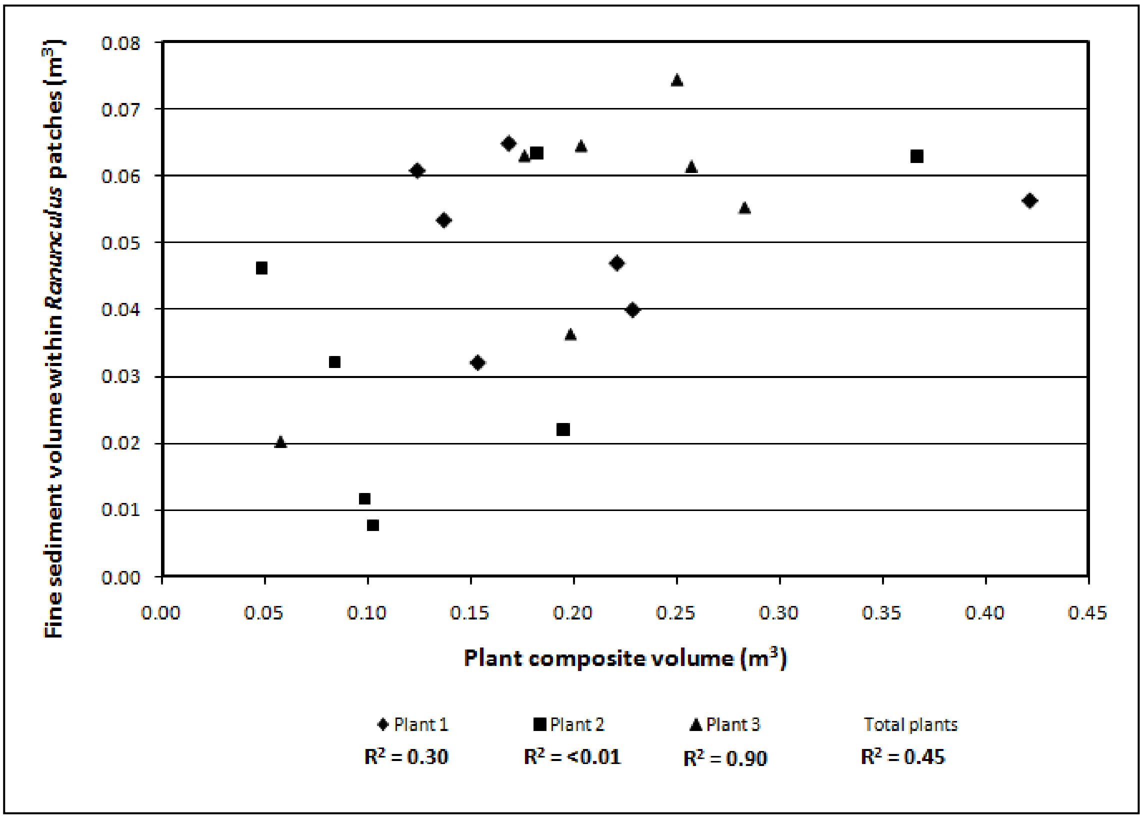


Figure 6.22 – A scatterplot showing the relationship between the plant composite volume (m^3) and fine sediment volume (m^3) within the three *Ranunculus* study patches on the River Frome at Frome Vauchurch. 'Total plants' represents the combined data from all three plants. The calculated coefficients of determination (R^2) are shown for all three plants and all of the datapoints combined.

6.1.3 Spatial and temporal differences of sediment characteristics within *Ranunculus* plants

Five sediment cores were retrieved from each of the three plants on both study reaches per sampling month, making a total of 15 sediment samples per study reach per sampling month. One core was extracted from each of the five specific zones identified within *Ranunculus* plants (see section 3.7.2). Samples were taken every two months from July 2008 to July 2009. This resulted in a total of 100 sediment samples taken from the Bere Stream and 105 samples taken from plants on the River Frome. Five sediment samples were missing from the Bere Stream due to the loss of plant 3 between the May 2009 and July 2009 survey month.

Sediment samples were analysed to estimate the following fine sediment characteristics: (1) the D_{50} of effective and absolute fine sediment; (2) the % volume of silt and clay sized particles within effective and absolute sediment samples; (3) the sorting of particles (S_0) within effective and absolute sediment samples; and (4) the % organic matter content within sediment samples. For further details of laboratory analyses see section 3.9.1.

Sediment samples taken from the Bere Stream were analysed separately from those taken from Frome Vauchurch. Sediment samples from each site were analysed on two levels. In the first level, samples from the same site were arranged into three groups corresponding with the three *Ranunculus* plants. At the second level all samples from the same site were sorted into five groups corresponding to the five zones rudimentarily identified within the *Ranunculus* patches.

A one-way analysis was used to determine if there were significant differences in the sediment characteristics between the three plants within each sample month. Datasets containing particle D_{50} values were considered to be non-parametric. An Andersen-Darling normality test was used to determine if other datasets from each plant were normally distributed because it is the most sensitive normality test for datasets with fewer than 20 samples (Dytham, 2003). Datasets containing percentage values were transformed using an arcsine transformation prior to any statistical analysis.

For normally distributed datasets a one-way ANOVA was used, for non-parametric datasets a Kruskal-Wallis test was used. A *post-hoc* analysis was performed if a significant difference was found in sediment characteristic values between the three plants to determine which was source of the significant difference. For normally distributed datasets a Fishers Least Significant Difference (LSD) analysis was used for *post-hoc* tests. For non-parametric datasets a series of Mann-Whitney U-tests were used to determine which plant had significantly different sediment characteristics between the three plants. The alpha level of significance was set at 0.05 for all of the statistical tests used.

Differences in sediment characteristics between sampling months were also analysed using a one-way test. The sediment characteristics from all three plants were compared between months using a one-way ANOVA for normally distributed data, or a Kruskal-Wallis test for non-parametric data. Again, *post-hoc* analyses were conducted to find out which of the sample months were significantly different to one another. For normally distributed data a Fishers LSD test was used, for non-parametric data a series of Mann-Whitney U-tests were conducted. The alpha level of significance was set at 0.05 for all of the statistical tests used.

Sediment characteristics were also analysed by the zone from which the sediment sample had been taken within the plant. A mean value for each zone was produced from three values, one from each of the three plants per sampling month. The mean value from July 2009 within the Bere Stream was comprised of just two values as plant 3 was lost in between the May 2009 and July 2009 survey months.

6.1.4 Variability in D_{50} particle sizes within *Ranunculus* plants on the Bere Stream

6.1.4.1 Changes in mean D_{50} values within the effective sediment fraction between *Ranunculus* plants

Differences in the mean D_{50} values of effective sediment between the three *Ranunculus* plants over the one year survey period are illustrated in Figure 6.23. The majority of mean D_{50} values within the effective sediment from all of the three plants were within the medium sand (250-500 μm). Only plant three had a mean D_{50} value within the fine sand (125-250 μm) in the September 2008 sample month. Plant two had the greatest mean D_{50} within effective sediment samples in the majority of the sample months, with the exception of July 2008, November 2008 and July 2009.

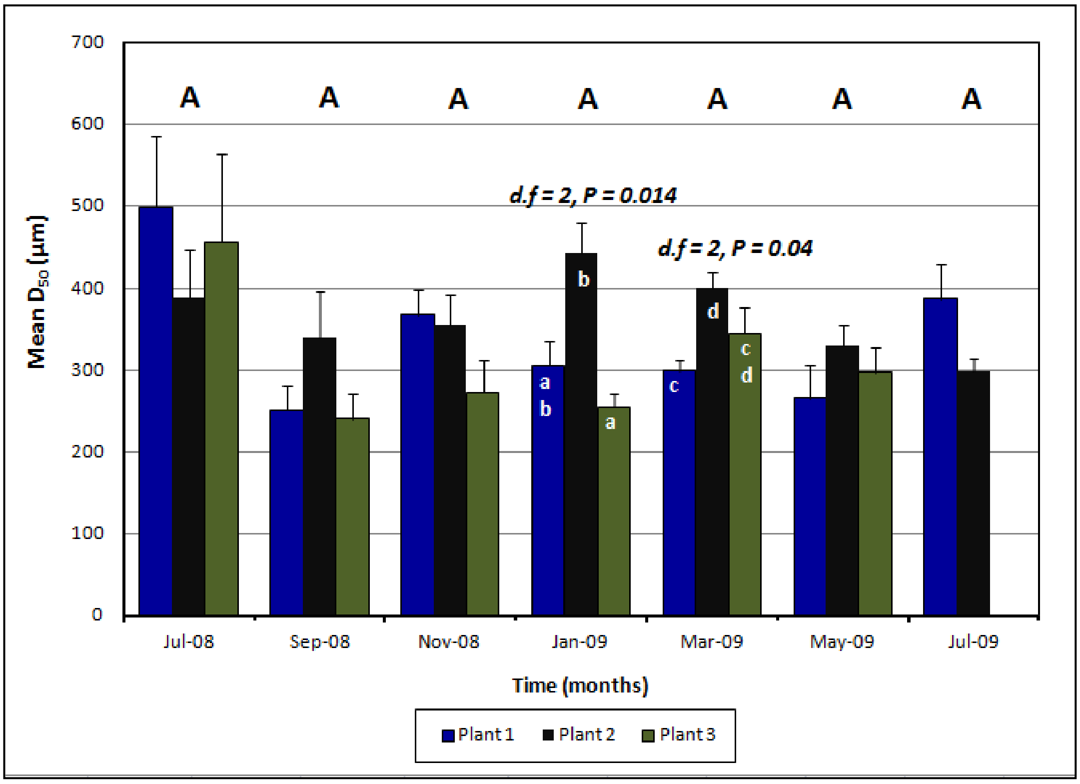


Figure 6.23 – The temporal changes in mean D_{50} of effective fine sediment within all three *Ranunculus* plants between July 2008 and July 2009 on the Bere Stream at Snatford Bridge. The whiskers on each bar indicate the standard error (SE). A ***P***-value is displayed within individual months where the three plants were statistically different for D_{50} values. The small-case letters within the bars indicate the results of a series of *post-hoc* Mann-Whitney U-tests that determined which of the three plants are significantly different to one another. Bars with the same letters were determined to be not significantly different to one another (***P*** >0.05). The large capital letters above the bars indicate the results of *post-hoc* Mann Whitney U-tests that determined which months were significantly different to one another when D_{50} values from all three plants within each month were combined and the values were compared between months. Months with the same capital letter indicate that they are not significantly different from one another (***P*** >0.05). In July 2009 the data for plant 3 is missing due to the loss of plant three before the July 2009 survey month.

The greatest mean D_{50} value within the effective sediment was found in July 2008 within plant one (499 ± 87 (SE) µm). The least mean D_{50} value from plant one was determined in September 2008 (251 ± 31(SE) µm); this was also the least mean D_{50} value between the three plants. Plant two had the greatest mean D_{50} in January 2009 (443 ± 38 (SE) µm), and the least mean D_{50} value in the July 2009 sample month at 298 ± 17 (SE) µm. The greatest value of mean D_{50} within plant three occurred in July 2008 (456 ± 109 (SE) µm), whilst the least value was in September 2008 (240 ± 32 (SE) µm).

A series of Kruskal-Wallis tests were used to test the differences in D_{50} values between the three plants within each sampling month (Figure 6.23). The D_{50} values of the three plants were found to be significantly different in January 2009 and March 2009 with *d.f* = 2, ***P*** = 0.014 and *d.f* = 2, ***P*** = 0.04 respectively. A series of *post-hoc* Mann-Whitney U-tests were conducted on the D_{50} between the three plants in January 2009 and March 2009. In the January 2009 sample month the D_{50} values from plant one and three were determined as not significantly different from one another, additionally values of particle D_{50} from plant one and two were not significantly different from one another. But the D_{50} values from plant two and three were significantly different to were significantly different to one another. In March 2009 the D_{50} values of plant one and three were found to not significantly differ from one another, whilst the D_{50} values of plant two and three were also found not to significantly differ. But the D_{50} values of plant one and two in March 2009 were found to be significantly different.

A further Kruskal-Wallis test determined there were no significant differences in D_{50} values between sample months using values from all three plants within each month (*d.f.* = *6*, ***P*** = 0.05). No further statistical analyses were conducted as the particle D_{50} values from each month were considered to be not significantly different.

6.1.4.2 Spatial and temporal differences in mean D_{50} values within the effective sediment fraction from *Ranunculus* plants

The variability of D_{50} values within effective sediment samples was compared between the five zones within *Ranunculus* plants. The mean D_{50} value for each zone was calculated from the three D_{50} values, each value was taken from the same corresponding zones within each of the three plants (Figure 6.24).

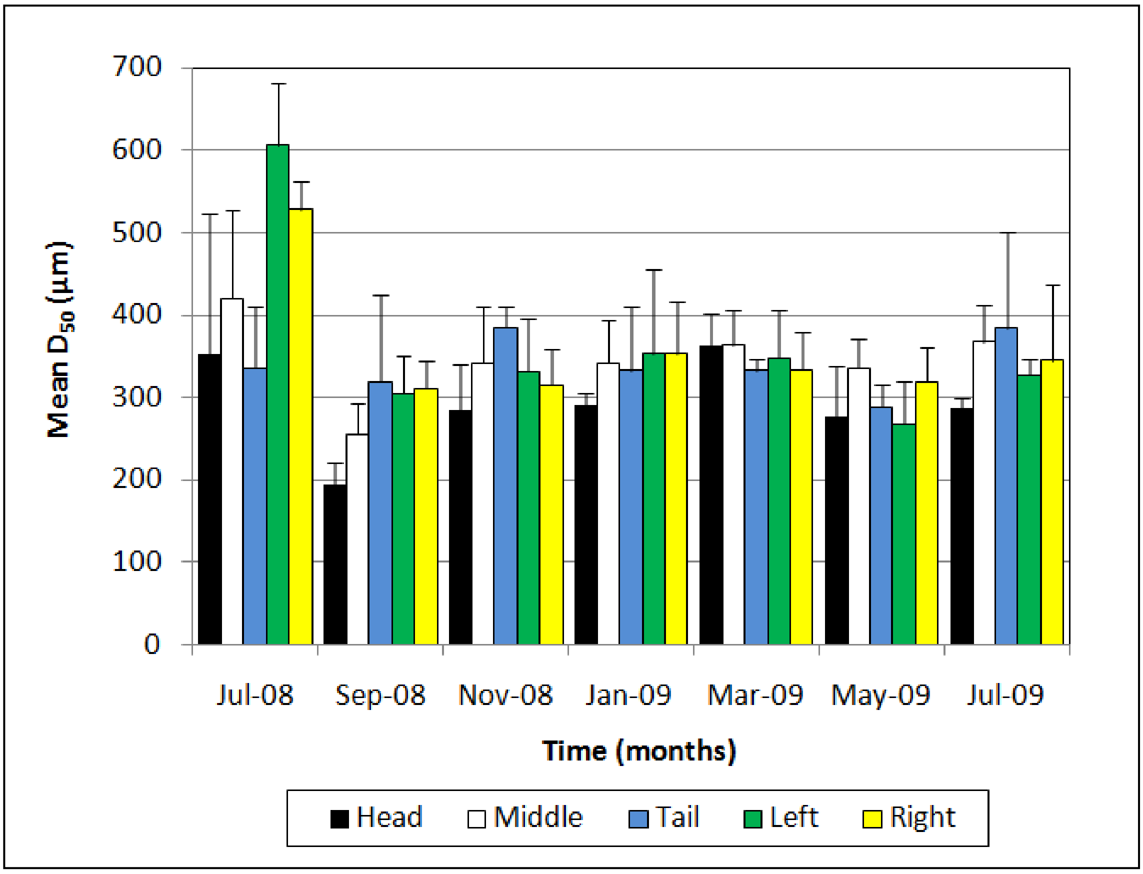


Figure 6.24 – Temporal differences in mean D_{50} of effective sediment between the five different zones investigated within *Ranunculus* patches on the Bere Stream at Snatford Bridge between July 2008 and July 2009. The mean value is comprised from three values, each taken from the same corresponding zone within each of the three plants. The whiskers on the bars represent the standard error (SE).

In general, all zones appeared to have similar mean D_{50} values and values of standard error throughout the one year sampling period. The majority of mean D_{50} values within the one year measurement period were within the medium sand (250-500 µm). However, there were a few mean D_{50} values taken in July 2008 and September 2008 that were different to the others. In July 2008 the mean D_{50} values of the left lateral and right lateral zones were within the coarse sand (500-1000 µm) at 606 ± 76 (SE) and 528 ± 35 (SE) µm correspondingly. In September 2008 the mean D_{50} value within the head zone was within the fine sand (125-250 µm) at 194 ± 27 (SE) µm, this made it the least mean D_{50} values within the entire one year dataset. In between November 2008 and July 2009 mean D_{50} values were within the medium sand from 267 to 385 µm.

6.1.4.3 Changes in the mean D_{50} values from the absolute sediment fraction between *Ranunculus* plants

Variations in mean D_{50} values of absolute sediment between the three *Ranunculus* plants over the one year survey period are illustrated in Figure 6.25. In the majority of months the values of mean D_{50} within absolute sediment from all of the three plants ranged from the fine to medium sand (125-500 µm). In the July 2008 sample month the mean D_{50} values of plant one and two were within the coarse sand (500-1000 µm). Between September 2008 and May 2009 plant two had the greatest mean D_{50} values between the three plants. In the July 2008 and July 2009 sample months the greatest mean D_{50} values were from plant one.

The greatest mean D_{50} value within absolute sediment samples was determined in July 2008 within plant one (595 ± 51 (SE) µm). The least mean D_{50} value from plant one was determined in July 2008 (368 ± 40 (SE) µm). Plant two had the greatest and least mean D_{50} in January 2009 and July 2009 at 445 ± 60 (SE) and 293 ± 10 (SE) µm respectively. The greatest value of mean D_{50} within plant three occurred in July 2008 (533 ± 105 (SE) µm), whilst the least value was in September 2008 (195 ± 32 (SE) µm). The months with the greatest and least mean D_{50} values for absolute sediment were the same as the greatest and least D_{50} values within the effective sediment for all three plants.

Kruskal-Wallis tests were used to analyse the differences in D_{50} values between the three plants within each sampling month (Figure 6.25). The D_{50} values of the three plants were found to be significantly different in January 2009 only (*d.f.* = 2, ***P*** = 0.02). A series of *post-hoc* Mann-Whitney U-tests were conducted on the values of D_{50} between the three plants in January 2009. In the January 2009 sample month the D_{50} values from plant one and three were determined as not significantly different to one another. But the D_{50} values of both plant one and three were significantly different to those of plant two.

A further Kruskal-Wallis test was used to test for significant differences in D_{50} values between the sample months using values from all three plants within each month. There was a highly significant difference (*d.f. = 6*, ***P*** <0.001) between all seven sample months for the values of D_{50} within the absolute sediment. The datasets were further treated with a series of *post-hoc* Mann-Whitney U-tests to reveal which sample months were significantly different to one another (Figure 6.25). The results from this analysis suggested that the D_{50} values for absolute sediment from July 2008 were significantly different (***P*** <0.003) to those from all of the other sample months.

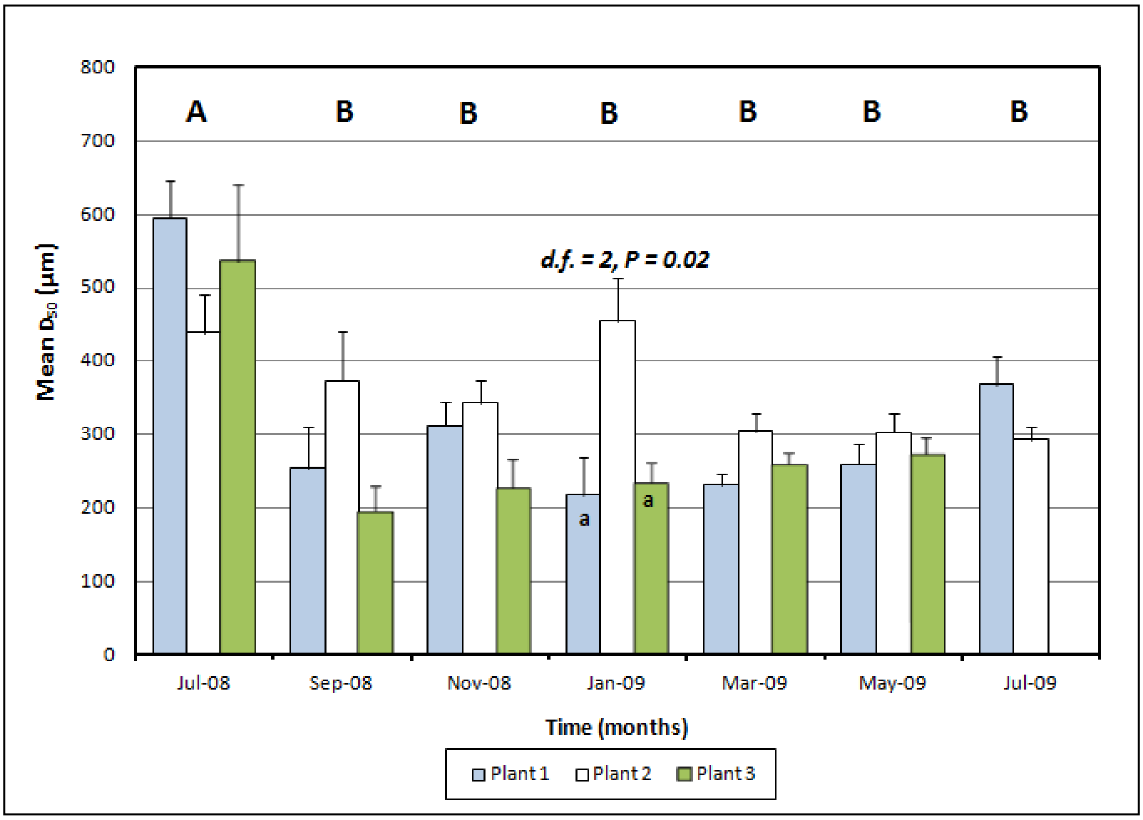


Figure 6.25 – The temporal changes in mean D_{50} of absolute fine sediment within all three *Ranunculus* plants between July 2008 and July 2009 on the Bere Stream at Snatford Bridge. The whiskers on each bar indicate the standard error (SE). A ***P***-value is displayed within individual months where the three plants were statistically different for D_{50} values. The small-case letters within the bars indicate the results of *post-hoc* Mann-Whitney U-tests that determined which of the three plants are significantly different to one another. Bars with the same letters were determined to be not significantly different to one another (***P*** >0.05). The large capital letters above the bars indicate the results of *post-hoc* Mann-Whitney U-tests that determined which months were significantly different to one another when D_{50} values from all three plants within each month were combined and the values were compared between months. Months with the same capital letter indicate that they are not significantly different from one another (***P*** >0.05). In July 2009 the data for plant 3 is missing due to the loss of plant three before the July 2009 survey month.

6.1.4.4 Spatial and temporal differences in mean D_{50} values within the absolute sediment fraction from *Ranunculus* plants

Variability of D_{50} values within absolute sediment samples was compared between the five zones within *Ranunculus* plants. The mean D_{50} value for each zone was calculated from the D_{50} values taken from the same corresponding zones within each of the three plants (Figure 6.26). All zones appeared to have similar values of mean D_{50} throughout the one year sampling period with the exception of the mean D_{50} values of the middle, tail, left and right lateral zones in July 2008. The zones in July 2008 were a considerable magnitude greater in comparison with the mean D_{50} values of zones within the other six sample months, being between the medium and coarse sand (250-1000 µm). In between November 2008 and July 2009 mean D_{50} values were between fine and medium sand (125-500 µm) from 235 to 401 µm. There appeared to be greater variability of D_{50} values within most of the five zones within the sample months

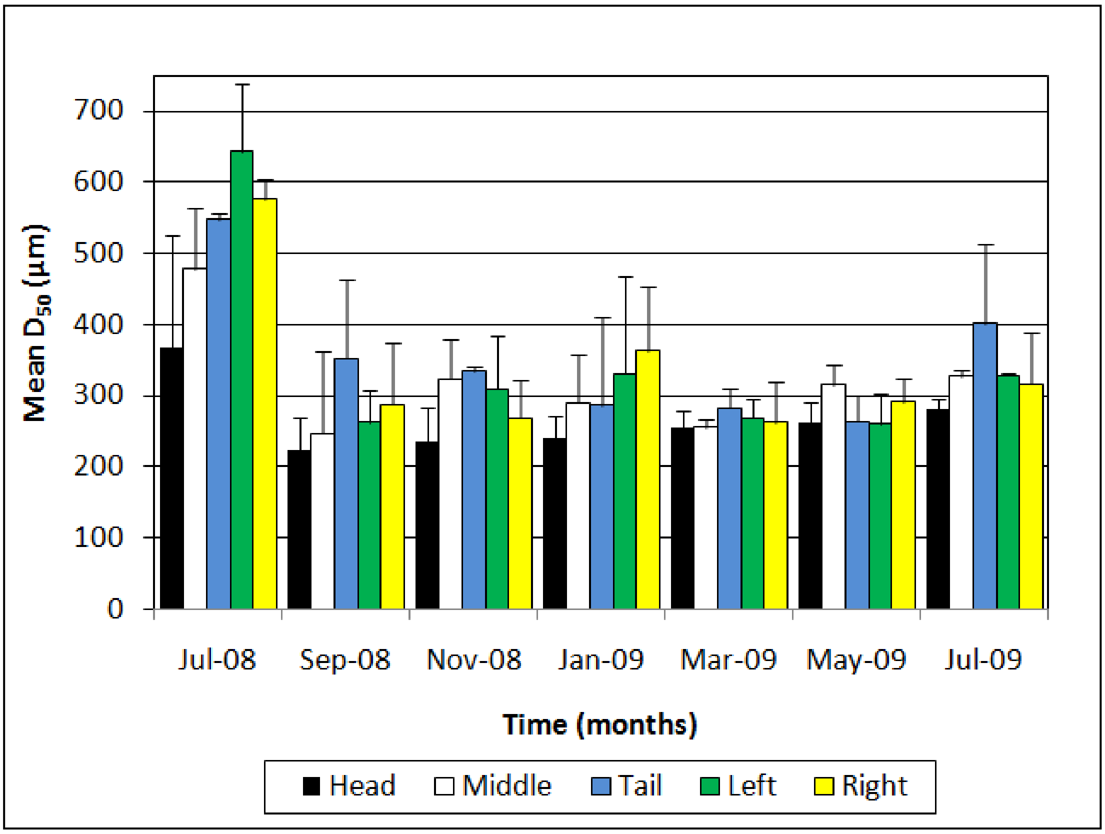


Figure 6.26 – Temporal differences in mean D_{50} of absolute sediment between the five different zones investigated within *Ranunculus* patches on the Bere Stream at Snatford Bridge between July 2008 and July 2009. The mean value is comprised from three values, each taken from the same corresponding zone within each of the three plants. The whiskers on the bars represent the standard error (SE).

between July 2008 and January 2009, as demonstrated by the standard error values (Figure 6.26).

The head zone appeared to possess the least mean D_{50} value consistently within each sample month. The mean D_{50} values for the absolute sediment within the head zone was within the fine sand in September 2008, November 2008 and January 2009 and in the medium sand within all of the other months.

The greatest mean D_{50} value within the entire dataset was observed in the left lateral zone in July 2008 at 643 ± 94 (SE) µm, whilst the least was the head zone in September 2008 at 247 ± 114 (SE) µm.

6.1.5 Variability in the % volume of silt and clay sized particles within *Ranunculus* plants on the Bere Stream

6.1.5.1 Changes in the mean % volume of silt and clay sized particles within the effective sediment fraction between *Ranunculus* plants

Temporal variability in mean % volume of silt and clay sized particles (mean %SC hereafter) within effective sediment between the three *Ranunculus* plants are illustrated in Figure 6.27. Mean %SC values of effective sediment from all of the three plants ranged between 4.7 and 12.5 %. All three plants had low values of mean %SC in July 2008 and conspicuously greater mean %SC values in May 2009. Values of mean %SC were noticeably greater in plants one and three compared with plant two between September 2008 and March 2009. The mean %SC values in plant two were <5.3 % between July 2008 and March 2009, with increases observed in May 2009 and July 2009.

The greatest mean %SC value within the effective sediment was from May 2009 within plant one (12.5 ± 2.1 (SE) %). The least mean %SC value from plant one was determined in July 2008 (4.8 ± 1.7 (SE) %). Plant two had the greatest mean %SC in May 2009 (9.7 ± 1.4 (SE) %), and the least mean %SC value in the January 2009 sample month at 4.7 ± 0.7 (SE) %. This was also the lowest mean %SC value between the three plants within the whole dataset. The greatest value of mean %SC within plant three occurred in May 2009 (9.2 ± 1.5 (SE) %), whilst the least value was in July 2008 (5.0 ± 2.5 (SE) %).

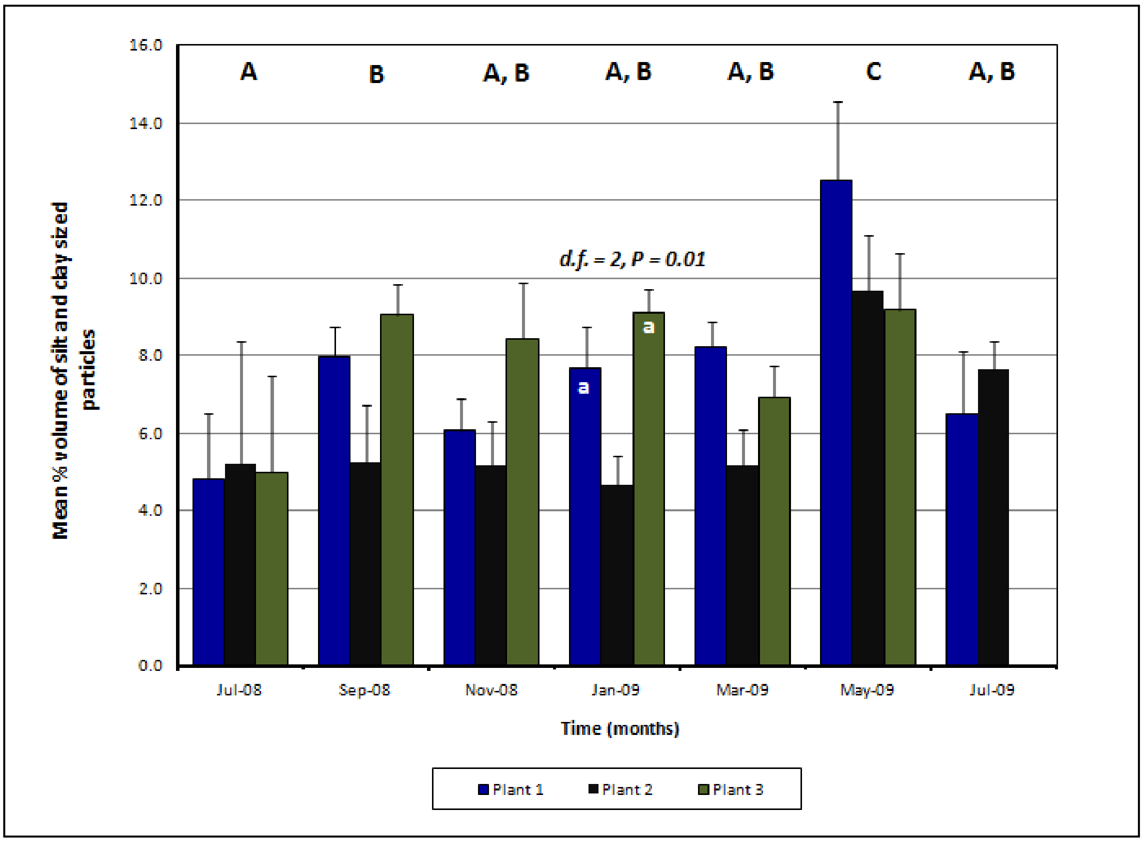


Figure 6.27 – The temporal changes in mean % volume of silt and clay sized particles (%SC) of effective fine sediment within all three *Ranunculus* plants between July 2008 and July 2009 on the Bere Stream at Snatford Bridge. The whiskers on each bar indicate the standard error (SE). A ***P***-value is displayed within individual months where the three plants were statistically different for %SC values. The small-case letters within the bars indicate the results of a *post-hoc* Fishers LSD test that determined which of the three plants are significantly different to one another. Bars with the same letters were determined to be not significantly different to one another (***P*** >0.05). The large capital letters above the bars indicate the results of a *post-hoc* Fishers LSD test that determined which months were significantly different to one another when %SC values from all three plants within each month were combined and the values were compared between months. Months with the same capital letter indicate that they are not significantly different from one another (***P*** >0.05). In July 2009 the data for plant 3 is missing due to the loss of plant three before the July 2009 survey month.

One-way ANOVAs were used to test the differences in %SC values between the three plants within each sampling month (Figure 6.27). The %SC values of the three plants were found to be significantly different in January 2009 (d.f. = 2, ***P*** = 0.01). A *post-hoc* Fishers LSD test was conducted on the %SC values between the three plants in January 2009. The analysis revealed that values of %SC from plant one and three were not significantly different from one another, but they were significantly different to those of plant two.

An additional one-way ANOVA was used to test for significant differences in %SC values between sample months using values from all three plants within each month. There was a highly significant difference (*d.f.* = *6*, ***P*** = 0.001) between all seven sample months for the values of %SC within the effective sediment. The datasets were further treated with a Fishers LSD *post-hoc* test to reveal which sample months were significantly different to one another (Figure 6.27). The results from this analysis suggested that the %SC values for effective sediment from May 2009 were significantly different to those from all of the other six sample months. In addition, %SC values of the effective sediment from September 2008 were significantly different to %SC values from July 2008.

6.1.5.2 Spatial and temporal differences in % volume of silt and clay-sized particles within the effective sediment fraction inside *Ranunculus* plants

The variability of %SC within effective sediment samples was compared between the five zones within *Ranunculus* plants. The mean %SC value for each zone was calculated from the %SC values taken from the same corresponding zones within each of the three plants (Figure 6.28).

Values of mean %SC within the entire one year dataset varied between 0.8 and 11.7 %. The middle, left and right lateral zone in July 2008 possessed the least values of mean %SC within the whole dataset. The least value of mean %SC was observed in the right lateral zone in July 2008 at 0.8 ± 0.5 (SE) %. The greatest mean %SC values of effective sediment within each zone were observed in the May 2009 sample month. The head zone possessed the greatest values of mean %SC in every sample month except March 2009, with the greatest value observed in May 2009 at 11.7 %.

6.1.5.3 Changes in the mean % volume of silt and clay sized particles within the absolute sediment fraction between *Ranunculus* plants

Temporal variability in mean %SC values within absolute sediment between the three *Ranunculus* plants are illustrated in Figure 6.29. Mean %SC values of absolute sediment from all of the three plants ranged between 3.9 and 21.5 %. All three plants had their lowest values of mean %SC in July 2008. Values of mean %SC were noticeably greater in plants one and three in comparison with plant two between September 2008 and January 2009.

The greatest mean %SC value within the absolute sediment was from plant three in September 2008 (21.5 ± 2.4 (SE) %). The least mean %SC value from plant three was determined in July 2008 (6.6 ± 5.9 (SE) %). Plant two had the greatest mean %SC

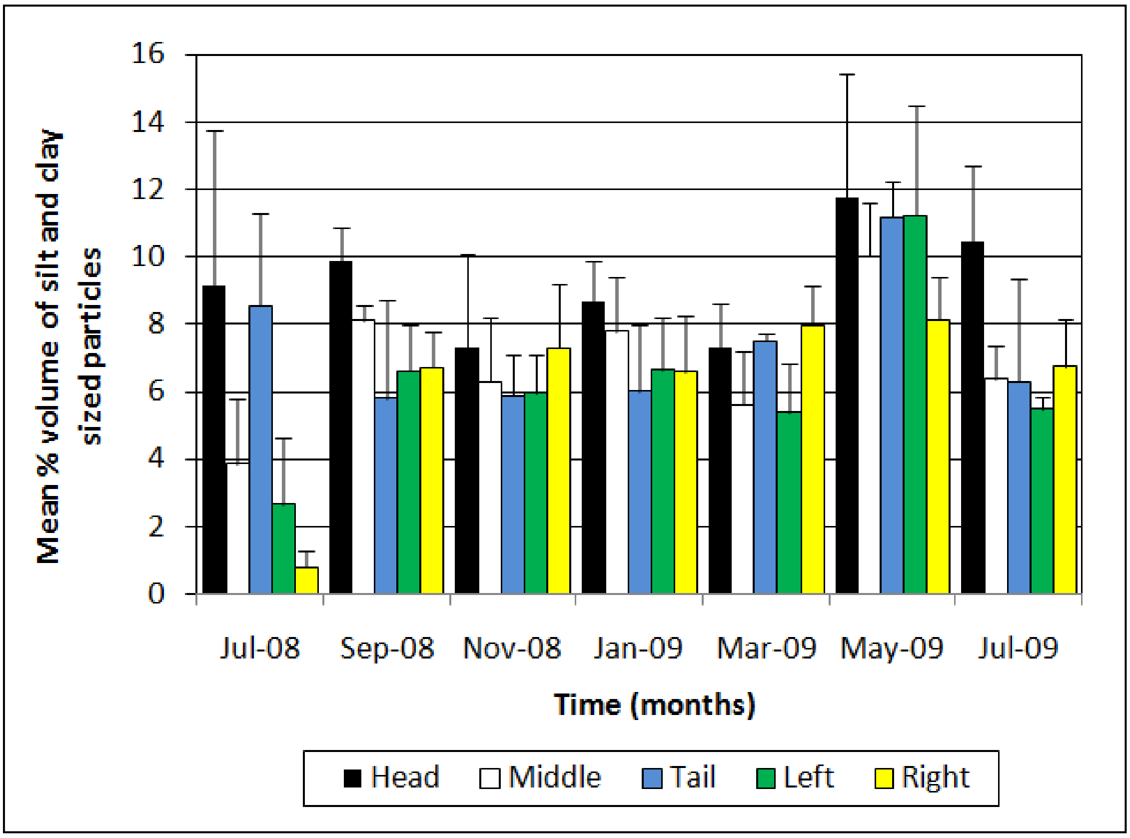


Figure 6.28 – Temporal differences in mean % volume of silt and clay sized particles (%SC) within the effective sediment from the five different zones investigated within *Ranunculus* patches on the Bere Stream at Snatford Bridge between July 2008 and July 2009. The mean value is comprised from three values, each taken from the same corresponding zone within each of the three plants. The whiskers on the bars represent the standard error (SE).

in March 2009 (11.0 ± 2.2 (SE) %), and the least mean %SC value in the July 2008 sample month at 3.9 ± 1.3 (SE) %. This was also the lowest mean %SC value between the three plants within the whole dataset. The greatest value of mean %SC within plant one occurred in September 2009 (19.9 ± 4.9 (SE) %), whilst the least value was in July 2008 (5.0 ± 2.5 (SE) %).

One-way ANOVA's were used to test the differences in %SC values between the three plants within each sampling month (Figure 6.29). The %SC values of the three

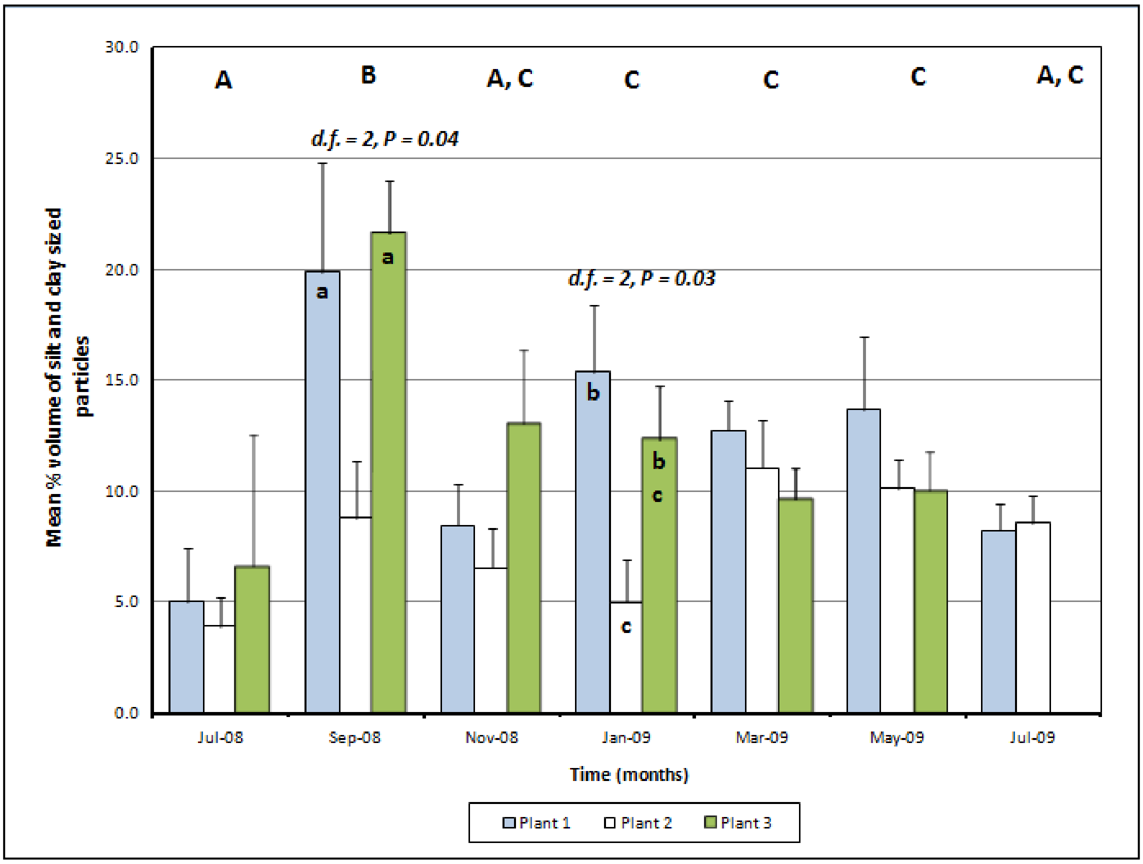


Figure 6.29 – The temporal changes in mean % volume of silt and clay sized particles (%SC) from absolute fine sediment within all three *Ranunculus* plants between July 2008 and July 2009 on the Bere Stream at Snatford Bridge. The whiskers on each bar indicate the standard error (SE). A ***P***-value is displayed within individual months where the three plants were statistically different for %SC values. The small-case letters within the bars indicate the results of a *post-hoc* Fishers LSD test that determined which of the three plants are significantly different to one another. Bars with the same letters were determined to be not significantly different to one another (***P*** >0.05). The large capital letters above the bars indicate the results of a *post-hoc* Fishers LSD test that determined which months were significantly different to one another when %SC values from all three plants within each month were combined and the values were compared between months. Months with the same capital letter indicate that they are not significantly different from one another (***P*** >0.05). In July 2009 the data for plant 3 is missing due to the loss of plant three before the July 2009 survey month.

plants were found to be significantly different in September 2008 and January 2009 at *d.f.* = 2, ***P*** = 0.04 and *d.f.* = 2, ***P*** = 0.03 respectively. A *post-hoc* Fishers LSD test was conducted on the %SC values between the three plants in September 2008. The analysis revealed that values of %SC from plant one and three were not significantly different from one another. However, the %SC values from plant one and three were significantly different to those of plant two. A further Fishers LSD analysis was conducted on the %SC values between the three plants in January 2009. The analysis revealed that %SC values from plant one and three were not significantly different from one another and % SC values from plant two and three were not significantly different from each other. But %SC values from plant one and two were significantly different from each other, and this was the source of variance in the one-way ANOVA.

An additional one-way ANOVA was used to test for significant differences in %SC values between sample months using values from all three plants within each month. There was a highly significant difference (*d.f.* = *6*, ***P*** = <0.001) between all seven sample months for the values of %SC within the absolute sediment. The datasets were further treated with a Fishers LSD *post-hoc* test to reveal which sample months were significantly different to one another (Figure 6.29). The results from this analysis suggested that the %SC values for absolute sediment from September 2008 were significantly different to those from all of the other six sample months. Furthermore, %SC values of the absolute sediment from July 2008 were significantly different to the %SC values from July 2008 January 2009, March 2009 and May 2009.

6.1.5.4 Spatial and temporal differences in % volume of silt and clay-sized particles within the absolute sediment fraction inside *Ranunculus* plants

The variability of %SC within absolute sediment samples was compared between the five zones within *Ranunculus* plants. The mean %SC value for each zone was calculated from the %SC values taken from the same corresponding zones within each of the three plants (Figure 6.30).

Values of mean %SC within the entire one year dataset ranged between 2.4 and 24.6 %. The tail, left and right lateral zones possessed the least values of mean %SC within the whole dataset at 2.7, 1.3 and 2.4 % respectively within the July 2008 sample month. The greatest mean %SC values of absolute sediment within each zone were observed in the September 2008 sample month with the middle zone possessing the greatest mean value of %SC within the absolute fractions of 24.6 ± 7.7 (SE) %. There were no general trends in any of the zones between the all of the sampled months. All of the five zones within each sample month appeared to possess similar mean %SC values from November 2008 to July 2009. However, the head zone is the only zone that possessed consistently higher values of %SC within the absolute sediment fraction from July 2008 to July 2009.

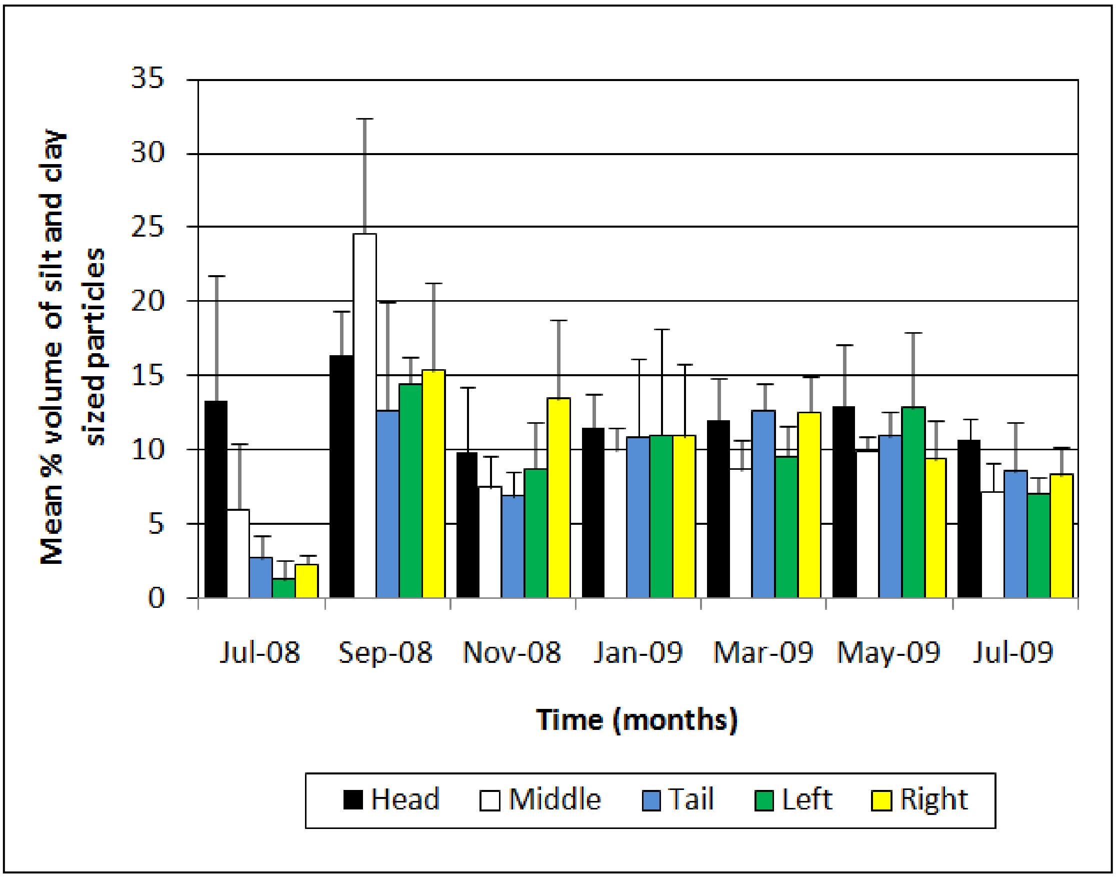


Figure 6.30 – Temporal differences in mean % volume of silt and clay sized particles (%SC) within the absolute sediment from the five different zones investigated within *Ranunculus* patches on the Bere Stream at Snatford Bridge between July 2008 and July 2009. The mean value is comprised from three values, each taken from the same corresponding zone within each of the three plants. The whiskers on the bars represent the standard error (SE).

6.1.6 Variability in particle sorting values within *Ranunculus* plants on the Bere Stream

The Trask sediment sorting coefficient (S_0) provides a measure of particle sorting within a sediment sample on a scale from 0 to 1, where 0 is not sorted to 1 which is very sorted (Trask, 1932). It was used to assess the extent of particle sorting within effective and absolute sediment samples taken from *Ranunculus* plants on the Bere Stream at Snatford Bridge.

6.1.6.1 Changes in particle sorting of the effective sediment fraction between *Ranunculus* plants

Variations in the mean S_0 values of effective sediment between the three *Ranunculus* plants over the one year survey period are illustrated in Figure 6.31. Mean S_0 values of effective sediment from all of the three plants ranged from 0.50 to 0.65. The effective sediment samples from plant two had the greatest mean S_0 values in all sample months from September 2008 to March 2009.

The greatest mean S_0 value within the effective sediment was found in January 2009 within plant two (S_0 0.65 ± 0.04 (SE)). The least mean S_0 value from plant two was determined in May 2009 as S_0 0.53 ± 0.02 (SE). The greatest mean value of S_0 from plant one occurred in July 2009 (S_0 0.62 ± 0.02 (SE)), and the least mean S_0 value from plant one was in the May 2009 sample month at S_0 0.50 ± 0.02 (SE). Additionally, this was also the smallest mean S_0 value within the entire dataset. The greatest value of mean S_0 within plant three occurred in July 2008 (S_0 0.64 ± 0.04 (SE)), whilst the least value was in September 2008 (S_0 0.51 ± 0.02 (SE)).

One-way ANOVA's were used to test the differences in S_0 values between the three plants within each sampling month (Figure 6.31). The S_0 values of the three plants were found to be significantly different in January 2009 only at *d.f* = 2, ***P*** = 0.001. A *post-hoc* Fishers LSD test conducted on the S_0 values between the three plants in January 2009 determined that S_0 values within plant one and plant three as not significantly different from one another. But the S_0 values from plant one and three were significantly different to those of plant two.

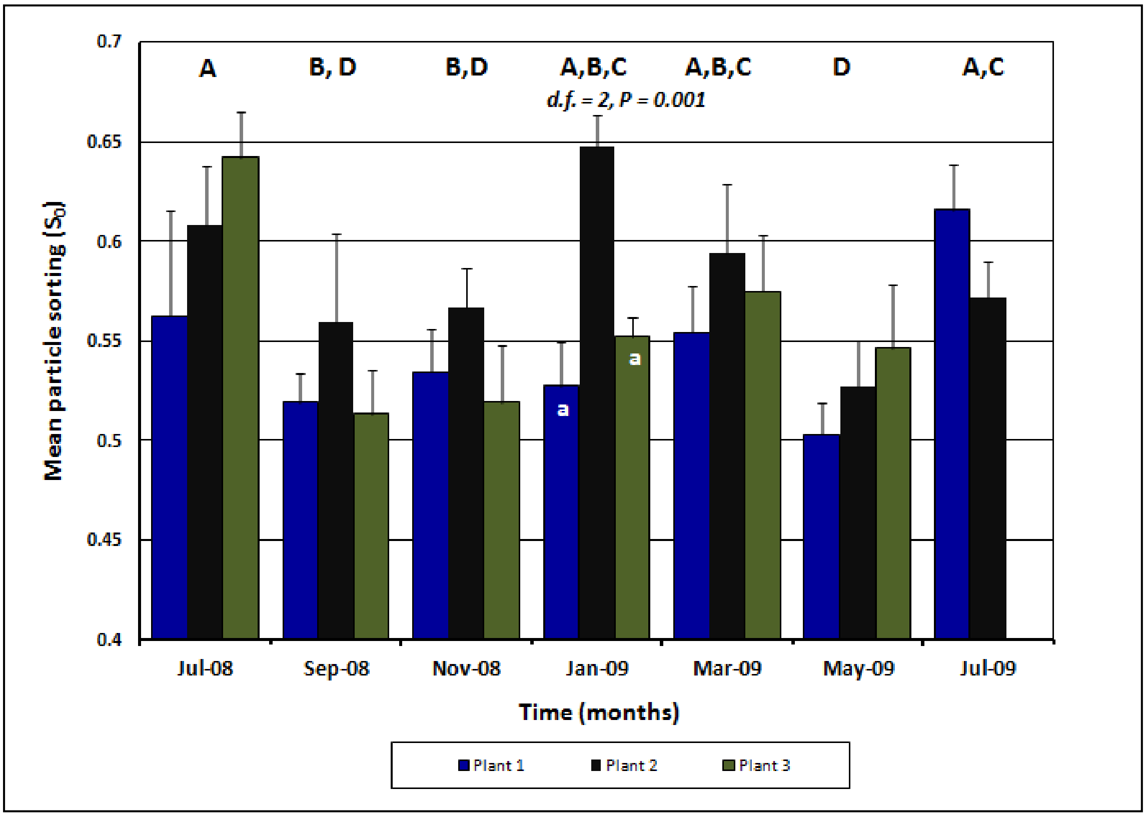


Figure 6.31 – The temporal changes in mean particle sorting (S_0) of effective fine sediment within all three *Ranunculus* plants between July 2008 and July 2009 on the Bere Stream at Snatford Bridge. The whiskers on each bar indicate the standard error (SE). A ***P***-value is displayed within individual months where the three plants were statistically different for S_0 values. The small-case letters within the bars indicate the results of a *post-hoc* Fishers LSD test that determined which of the three plants are significantly different to one another. Bars with the same letters were determined to be not significantly different to one another (***P*** >0.05). The large capital letters above the bars indicate the results of a *post-hoc* Fishers LSD test that determined which months were significantly different to one another when S_0 values from all three plants within each month were combined and the values were compared between months. Months with the same capital letter indicate that they are not significantly different from one another (***P*** >0.05). In July 2009 the data for plant 3 is missing due to the loss of plant three before the July 2009 survey month.

A further one-way ANOVA was used to test for significant differences in S_0 values between sample months using values from all three plants within each month. There was a highly significant difference (*d.f* = 6, ***P*** = 0.004) between all seven sample months for the values of S_0 within the effective sediment. The datasets were further treated with a Fishers LSD *post-hoc* test to reveal which sample months were significantly different to one another (Figure 6.31). The results from this analysis suggested that the S_0 values for effective sediment from July 2008 were significantly different to values from September 2008, November 2009 and May 2009. In addition, S_0 values of the effective sediment from May 2009 were significantly different to all other sample months except September 2008 and November 2008. Also, the S_0 values from July 2009 were significantly different to S_0 values from September 2008, November 2008 and May 2009.

6.1.6.2 Spatial and temporal differences in particle sorting within the effective sediment fraction inside *Ranunculus* plants

The variability of S_0 values within effective sediment samples was compared between the five zones within *Ranunculus* plants. The mean S_0 value for each zone was calculated from the S_0 values taken from the same corresponding zones within each of the three plants (Figure 6.32). In general, all zones appeared to have similar mean S_0 values and values of standard error throughout the one year sampling period. Mean S_0 values were between 0.49 and 0.63. The middle zone in the May 2009 sample month had the least mean S_0 value (S_0 0.49 ± 0.03 (SE)), and the right lateral zone in the July 2008 sample month had the greatest value (S_0 0.63 ± 0.04 (SE)). There were no conspicuous temporal patterns present in the mean S_0 values from each zone. However, the mean S_0 values from some of the zones appeared to be slightly lower in the months of September 2008, November 2008 and May 2009.

6.1.6.3 Changes in particle sorting within the absolute sediment fraction inside *Ranunculus* plants

Variations in the mean S_0 values of absolute sediment between the three *Ranunculus* plants over the one year survey period are illustrated in Figure 6.33. Mean S_0 values of absolute sediment from all of the three plants ranged from 0.45 to 0.69.

The greatest mean S_0 value within the absolute sediment was found in July 2008 within plant one (S_0 0.69 ± 0.06 (SE)). The least mean S_0 value from plant one was determined in September 2008 (S_0 0.45 ± 0.01 (SE)), this was also the smallest mean S_0 value within the entire dataset. The greatest mean S_0 value from plant two occurred in July 2008 (S_0 0.68 ± 0.02 (SE)), and the least mean S_0 value from plant two was in the

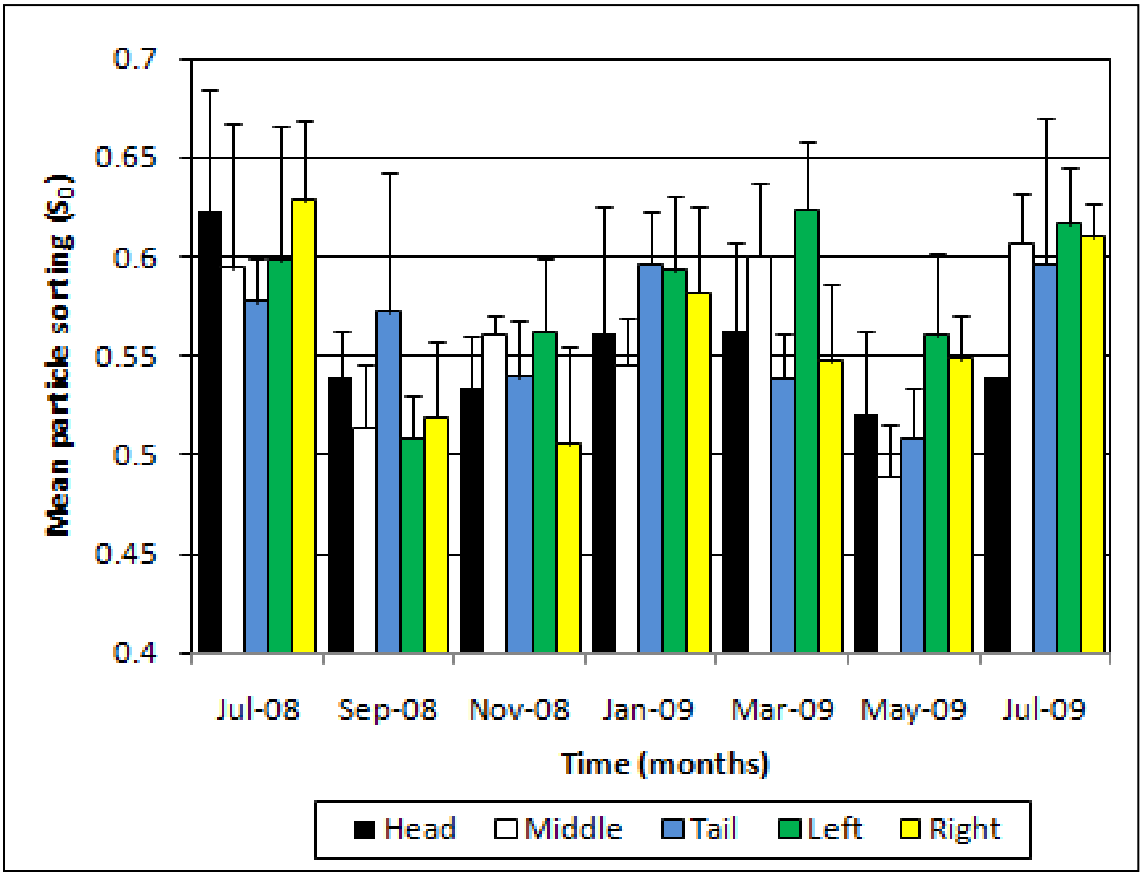


Figure 6.32 – Temporal differences in mean particle sorting (S_0) within the effective sediment from the five different zones investigated within *Ranunculus* patches on the Bere Stream at Snatford Bridge between July 2008 and July 2009. The mean value is comprised from three values, each taken from the same corresponding zone within each of the three plants. The whiskers on the bars represent the standard error (SE).

September 2008 sample month at S_0 0.55 ± 0.05 (SE). The greatest value of mean S_0 within plant three occurred in July 2008 (S_0 0.67 ± 0.08 (SE)), whilst the least value was in September 2008 (S_0 0.46 ± 0.03 (SE)). All of the greatest mean S_0 values within the three plants occurred within the July 2008 sample month. This was followed by all of the least mean S_0 values within all three plants in September 2008. Aside from this there were no seasonal patterns in mean S_0 values within any of the three plants.

No significant differences were found between the three plants with respect to S_0 values within individual sample months. This suggests that the S_0 values of the three plants were similar within each sampling month.

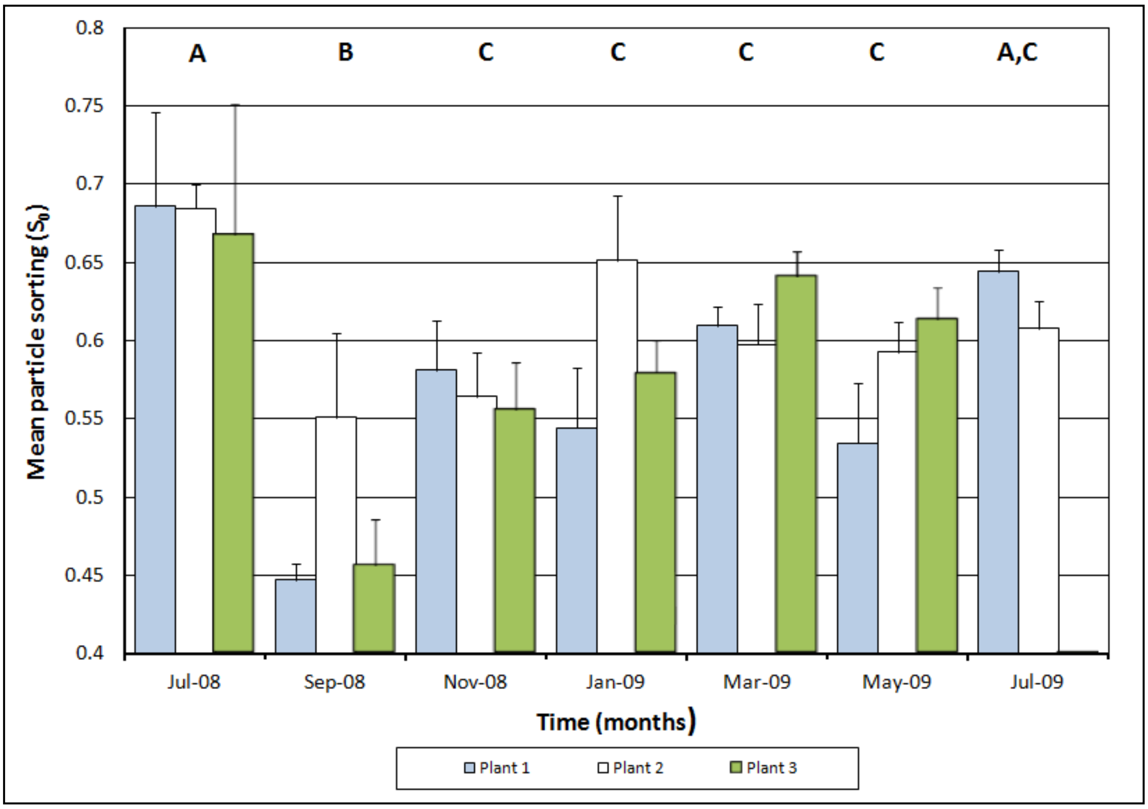


Figure 6.33 – The temporal changes in mean particle sorting (S_0) of absolute fine sediment within the three *Ranunculus* plants between July 2008 and July 2009 on the Bere Stream at Snatford Bridge. The whiskers on each bar indicate the standard error (SE). A ***P***-value is displayed within individual months where the three plants were statistically different for S_0 values. The small-case letters within the bars indicate the results of a *post-hoc* Fishers LSD test that determined which of the three plants are significantly different to one another. Bars with the same letters were determined to be not significantly different to one another (***P*** >0.05). The large capital letters above the bars indicate the results of a *post-hoc* Fishers LSD test that determined which months were significantly different to one another when S_0 values from all three plants within each month were combined and the values were compared between months. Months with the same capital letter indicate that they are not significantly different from one another (***P*** >0.05). In July 2009 the data for plant 3 is missing due to the loss of plant three before the July 2009 survey month.

A one-way ANOVA was used to test for significant differences in S_0 values between sample months using values from all three plants within each month. There was a highly significant difference (*d.f.* = *6*, ***P*** <0.001) between all seven sample months for the values of S_0 within the absolute sediment. The datasets were further treated with a Fishers LSD *post-hoc* test to reveal which sample months were significantly different to one another (Figure 6.33). The results from this analysis suggested that the S_0 values for absolute sediment from July 2008 were significantly different to values of S_0 from all other months with the exception of July 2009. In addition, S_0 values of the absolute sediment from September 2008 were significantly different to S_0 values within all other sample months. The analysis also determined that all of the sample months from November 2008 to July 2009 were not significantly different to one another for their respective values of S_0.

6.1.6.4 Spatial and temporal differences in particle sorting within the absolute sediment fraction inside *Ranunculus* plants

The variability of S_0 values within the absolute sediment samples was compared between the five zones identified within *Ranunculus* plants. The mean S_0 value for each zone was calculated from the S_0 values taken from the same corresponding zones within each of the three plants (Figure 6.34). In general, all zones appeared to have similar mean S_0 values and associated values of standard error throughout the one year sampling period. The lowest mean S_0 values of the head, middle, tail and left lateral zones were present within the September 2008 sample month. Additionally, the greatest mean S_0 values for the tail zone, left lateral zone and right lateral zone were observed in the July 2008 sample month. The mean S_0 values from the July 2008 sample month demonstrated the most variability in between zones within the *Ranunculus*. The tail zone in the July 2009 sample month had the greatest mean S_0 value (S_0 0.78 ± 0.04 (SE)), and the middle zone in the September 2008 sample month had the least value (S_0 0.43 ± 0.04 (SE)). The range between mean S_0 values within the absolute fraction was considerably greater than the range between the mean S_0 values of the effective fraction.

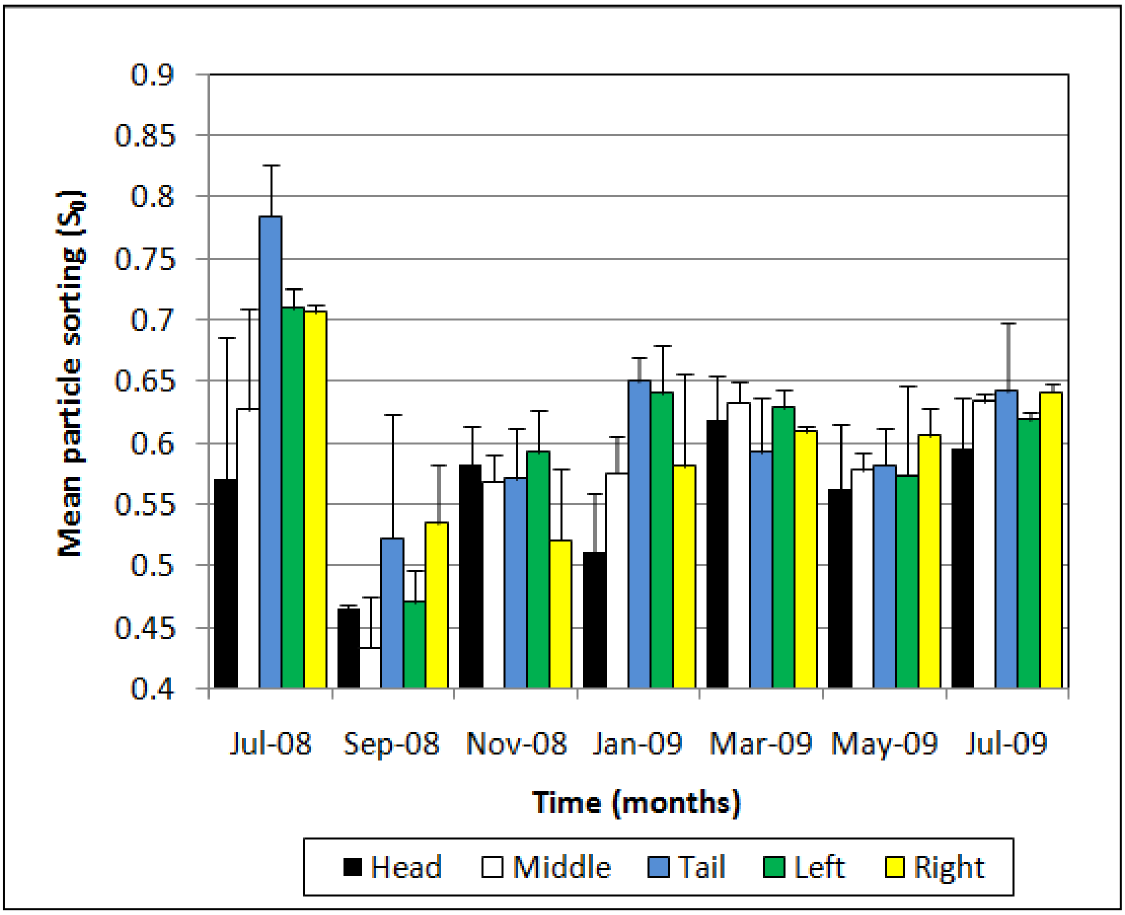


Figure 6.34 – Temporal differences in mean particle sorting (S_0) within the absolute sediment from the five different zones investigated within *Ranunculus* patches on the Bere Stream at Snatford Bridge between July 2008 and July 2009. The mean value is comprised from three values, each taken from the same corresponding zone within each of the three plants. The whiskers on the bars represent the standard error (SE).

6.1.7 Variability in the organic matter content within *Ranunculus* plants on the Bere Stream

6.1.7.1 Changes in the % organic matter of sediment between *Ranunculus* plants

The variability of mean % organic matter content (%OM hereafter) between the three *Ranunculus* plants over the one year survey period are illustrated in Figure 6.35. Mean %OM values of sediment from all of the three plants ranged from 1.4 to 9.7 %. Mean %OM values from plant one and three appeared to be similar in the majority of the sample months, including September 2008 when both plants had noticeably high mean %OM values.

The greatest mean %OM value was found in September 2008 within plant three (9.7 ± 3.4 (SE) %). The least mean %OM value from plant three was determined in March 2009 (2.6 ± 0.7 (SE) %). Plant one had the greatest mean %OM in September 2008 (7.7 ± 4.6 (SE) %), and the least mean %OM value in the July 2009 sample month at 1.6 ± 0.3 (SE) %. The mean values of %OM in plant two appeared to possess less variation throughout the seven month sampling period in comparison with the mean %OM values of plant one and three. The greatest mean %OM within plant two occurred in March 2009 (3.5 ± 1.7 (SE) %), whilst the least mean %OM value was in January 2009 (1.4 ± 0.2 (SE) %).

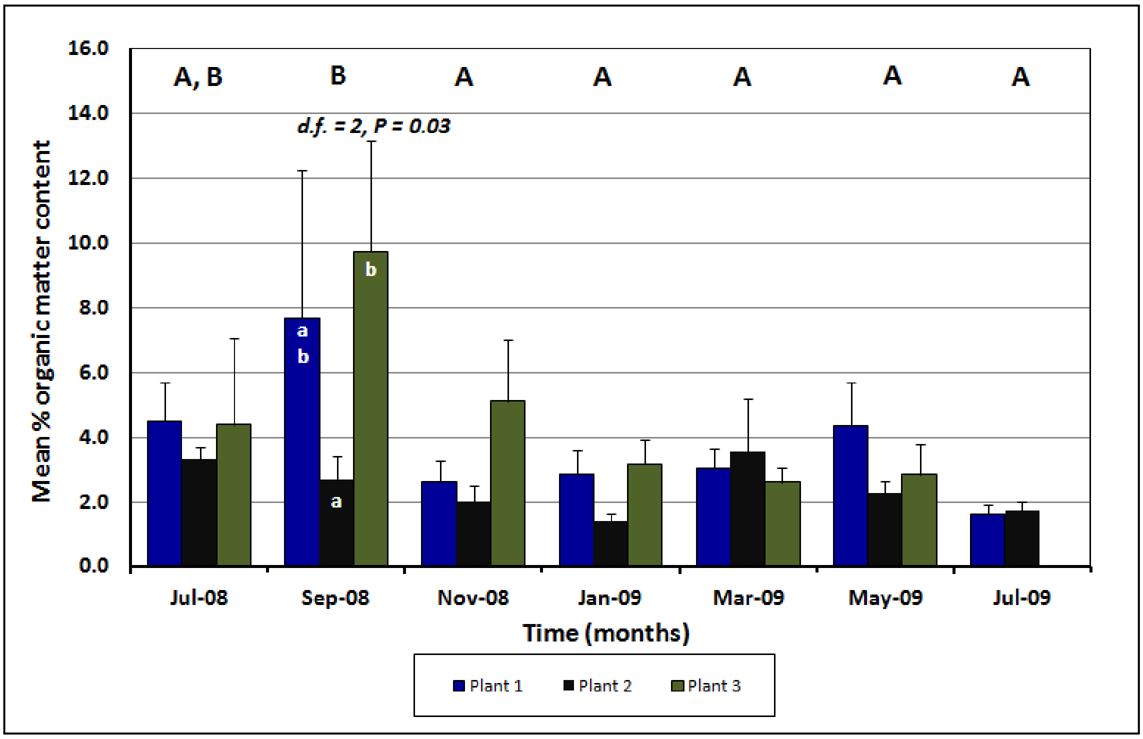


Figure 6.35 – The temporal changes in mean % organic matter (%OM) of fine sediment within the three *Ranunculus* plants between July 2008 and July 2009 on the Bere Stream at Snatford Bridge. The whiskers on each bar indicate the standard error (SE). A ***P***-value is displayed within individual months where the three plants were statistically different for %OM values. The small-case letters within the bars indicate the results of *post-hoc* Mann-Whitney U-tests that determined which of the three plants are significantly different to one another. Bars with the same letters were determined to be not significantly different to one another (***P*** >0.05). The large capital letters above the bars indicate the results of *post-hoc* Mann-Whitney U-tests that determined which months were significantly different to one another when %OM values from all three plants within each month were combined and the values were compared between months. Months with the same capital letter indicate that they are not significantly different from one another (***P*** >0.05). In July 2009 the data for plant 3 is missing due to the loss of plant three before the July 2009 survey month.

A series of Kruskal-Wallis analyses were used to test the differences in %OM values between the three plants within each sampling month (Figure 6.35). The %OM values of the three plants were found to be significantly different in January 2009 only (*d.f.* = 2, ***P*** = 0.03). A series of *post-hoc* Mann-Whitney U-tests were conducted on the %OM values between the three plants in January 2009. The %OM values from plant one and three were determined as not significantly different from one another, and the %OM values from plant one and two were also determined to be not significantly different. But the %OM values from plant two and three were determined to be significantly different to one another.

A further Kruskal-Wallis analysis was used to test for significant differences in %OM values between sample months using values from all three plants within each month. There was a significant difference (*d.f.* = 6, ***P*** = 0.02) between all seven sample months for the values of %OM within the sediment samples. The datasets were further treated with a series of *post-hoc* Mann-Whitney U-tests to reveal which sample months were significantly different to one another (Figure 6.35). The results from these analyses suggested that the %OM values from September 2008 were significantly different to all the %OM values within all other sample months except the %OM values in July 2008.

6.1.7.2 Spatial and temporal differences in the % organic matter of sediment within *Ranunculus* plants

The variability of %OM values from the sediment samples were compared between the five zones within *Ranunculus* plants. The mean %OM value for each zone was calculated from the inclusion of %OM values taken from the same corresponding zones within each of the three plants (Figure 6.36).

In general, all five zones appeared to have similar mean %OM values and values of standard error throughout the one year sampling period. Mean %OM values generally ranged between 1.2 and 4.7 % in the majority of zones within the seven sample months. There were a number of zones that did have conspicuously high values of mean %OM. The middle zone within the September 2008 sample month had the greatest mean value of %OM and the greatest standard error estimation (11.4 ± 7.3 (SE)

%). This was closely followed by the right lateral zone also in the September 2008 sample month which possessed a considerably high mean %OM value and associated standard error estimation (9.5 ± 6.9 (SE) %). The zone with the least value of mean %OM was the middle zone in the July 2009 sample month at 1.2 ± 0.01 (SE) %. Additionally, only the head zone in the July 2009 sample month had a mean %OM value of greater than 2 %. Mean %OM values for the middle, left and right lateral zones that appeared to vary the most within the one year study period.

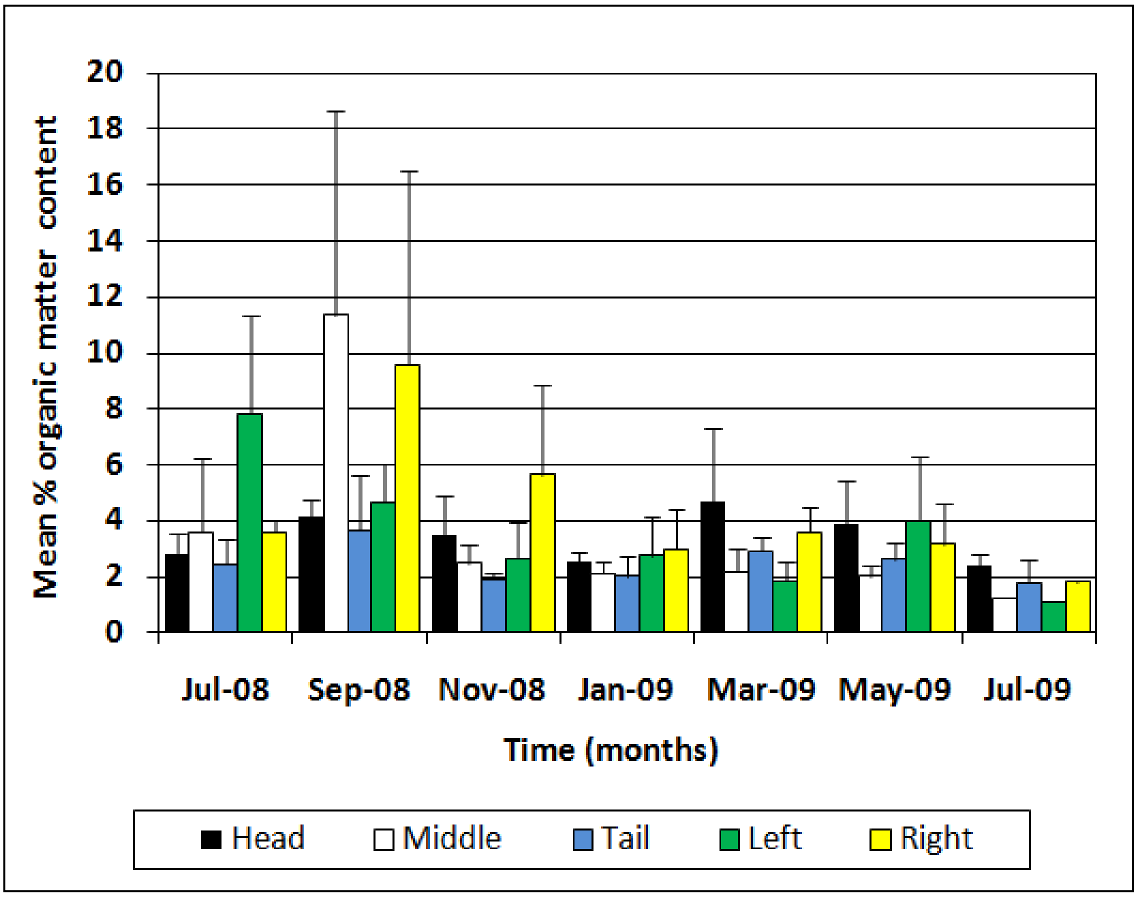


Figure 6.36 – Temporal differences in mean % organic matter content (%OM) within the sediment from the five different zones investigated within *Ranunculus* patches on the Bere Stream at Snatford Bridge between July 2008 and July 2009. The mean value is comprised from three values, each taken from the same corresponding zone within each of the three plants. The whiskers on the bars represent the standard error (SE).

6.1.8 Variability in D_{50} values within *Ranunculus* plants on the River Frome

6.1.8.1 Changes in the mean D_{50} values within the effective sediment fraction between *Ranunculus* plants at Frome Vauchurch

Differences in the mean D_{50} values of effective sediment between the three *Ranunculus* plants over the one year survey period are illustrated in Figure 6.37. Mean D_{50} values of effective sediment from all of the three plants ranged from the fine to medium sand (125-500 μm). Mean D_{50} values from plant three were within the fine sand (125-250 μm) throughout the one year period. Mean D_{50} values from plant one were within the medium sand from July 2008 to March 2009 and the fine sand in the May 2009 and July 2009 sample months. Plant two had mean D_{50} values within the medium sand from July 2008 to May 2009, with the mean value of D_{50} in July 2009 being within the fine sand. Additionally, plant two had the greatest mean D_{50} within effective sediment samples in all of the sample months except July 2009. Plant two showed the greatest variability between its samples for D_{50} within the effective sediment, as demonstrated by the higher standard error values.

The greatest mean D_{50} value within the effective sediment was from plant two in the July 2008 sample month (476 ± 138 (SE) μm). The least mean D_{50} value from plant two was determined in July 2009 (208 ± 20 (SE) μm). The greatest mean D_{50} value from plant one was determined in the July 2008 sample month (430 ± 88 (SE) μm), whilst the least mean D_{50} value from plant one was from the July 2009 sample month at 234 ± 71 (SE) μm. The greatest value of mean D_{50} within plant three occurred in July 2008 (456 ± 109 (SE) μm), whilst the least value was in July 2008 (229 ± 22 (SE) μm). Overall plant three appeared to have the least variable mean D_{50} values throughout the one year period.

Kruskal-Wallis analyses were used to test the differences in D_{50} values between the three plants within each sampling month (Figure 6.37). The D_{50} values of the three plants were found to be significantly different in November 2008, March 2009 and May 2009 at *d.f.* = 2, ***P*** = 0.01, *d.f.* = 2, ***P*** = 0.03 and *d.f.* = 2, ***P*** = 0.01 respectively. A series of *post-hoc* Mann-Whitney U-tests were conducted on the D_{50} between the three plants in November 2008, March 2009 and May 2009. In the November 2008 sample month the D_{50} values from plant one and two were determined as not significantly different from one another. But the D_{50} values from plant three were significantly different to the D_{50} values from plant one and plant two. In March 2009 the D_{50} values of plant one and two were found to not significantly differ from one another, and the D_{50} values of plant two and three were also found not to significantly differ. But the D_{50} values of plant one and three were found to be significantly different. In the May 2009 sample month D_{50} values from plant one and two were found not to significantly differ from one another, but the D_{50} values from plant three were significantly different to those from both plant one and two.

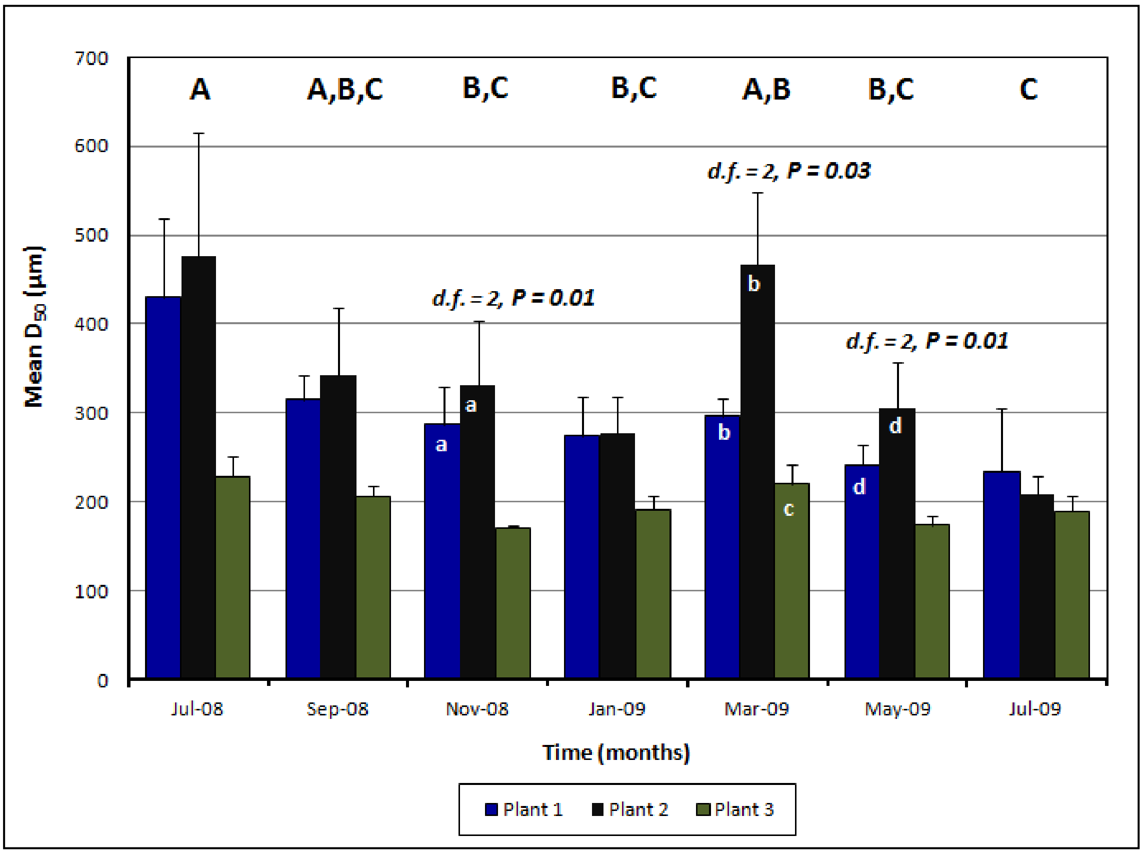


Figure 6.37 – The temporal changes in mean D_{50} of effective fine sediment within all three *Ranunculus* plants between July 2008 and July 2009 on the River Frome at Frome Vauchurch. The whiskers on each bar indicate the standard error (SE). A ***P***-value is displayed within individual months where the three plants were statistically different for D_{50} values. The small-case letters within the bars indicate the results of *post-hoc* Mann-Whitney U-tests that determined which of the three plants are significantly different to one another. Bars with the same letters were determined to be not significantly different to one another (***P*** >0.05). The large capital letters above the bars indicate the results of a *post-hoc* Mann-Whitney U-tests that determined which months were significantly different to one another when D_{50} values from all three plants within each month were combined and the values were compared between months. Months with the same capital letter indicate that they are not significantly different from one another (***P*** >0.05).

A further Kruskal-Wallis test used to investigate significant differences in D_{50} values between sample months using values from all three plants within each month. A significant difference was found between the sample months for their values of D_{50} (*d.f.* = *6*, ***P*** = 0.01). A further series of *post-hoc* Mann-Whitney U-tests were conducted to determine which of the months were significantly different to one another (Figure 6.37). The D_{50} values from July 2008 were significantly different to those from November 2008, January 2009, May 2009 and July 2009. Additionally, the D_{50} values from July 2009 were significantly different to those from March 2009.

6.1.8.2 Spatial and temporal differences in mean D_{50} values within the effective sediment fraction inside *Ranunculus* plants at Frome Vauchurch

The variability of D_{50} values within effective sediment samples was compared between the five zones within *Ranunculus* plants. The mean D_{50} value for each zone was calculated from the three D_{50} values, each value was taken from the same corresponding zones within each of the three plants (Figure 6.38).

In general, all zones appeared to have similar mean D_{50} values and values of standard error throughout the one year sampling period with no seasonal pattern emerging from the dataset. The majority of mean D_{50} values ranged between the fine and medium sand (125-500 µm), with only the tail zone in July 2008 possessing a mean D_{50} value in the coarse sand (574 ± 186 (SE) µm). This was also the greatest mean D_{50} value within the one year dataset. The head zone in the July 2009 sample month possessed the least mean D_{50} value within the one year dataset (165 ± 6 (SE) µm).

6.1.8.3 Changes in the mean D_{50} within the absolute sediment fraction between *Ranunculus* plants on the River Frome

Variations in the mean D_{50} values of absolute sediment between the three *Ranunculus* plants over the one year survey period are illustrated in Figure 6.39. From November 2008 to July 2009 the majority of mean D_{50} values within the absolute sediment from all three plants were within the fine sand (125-250 µm), with the exception of plant one in January 2009 and plant one and two in May 2009 which were in the medium sand. Within the July 2008 and September 2008 sample months the majority of mean D_{50} values were in the medium sand (250-500 µm) with the exception of the mean D_{50} value of plant three in September 2008. The July 2008 sample month had the greatest D_{50} sample variance within each of the three plants, as indicated by the standard error.

The greatest mean D_{50} value within absolute sediment samples was determined in September 2008 within plant two (444 ± 76 (SE) µm). The least mean D_{50} value from plant two was determined in July 2009 (159 ± 16 (SE) µm). Plant one had its greatest and least mean D_{50} in July 2008 (429 ± 111 (SE) µm) and July 2008 (429 ± 111 (SE) µm) respectively. The greatest value of mean D_{50} from plant three occurred in July 2008 (418 ± 140 (SE) µm), whilst the least value was in November 2008 (164 ± 5 (SE) µm).

Kruskal-Wallis tests were used to investigate differences in D_{50} values between the three plants within each sampling month (Figure 6.39). No significant differences were determined between the three plants regarding D_{50} values within any of the sample

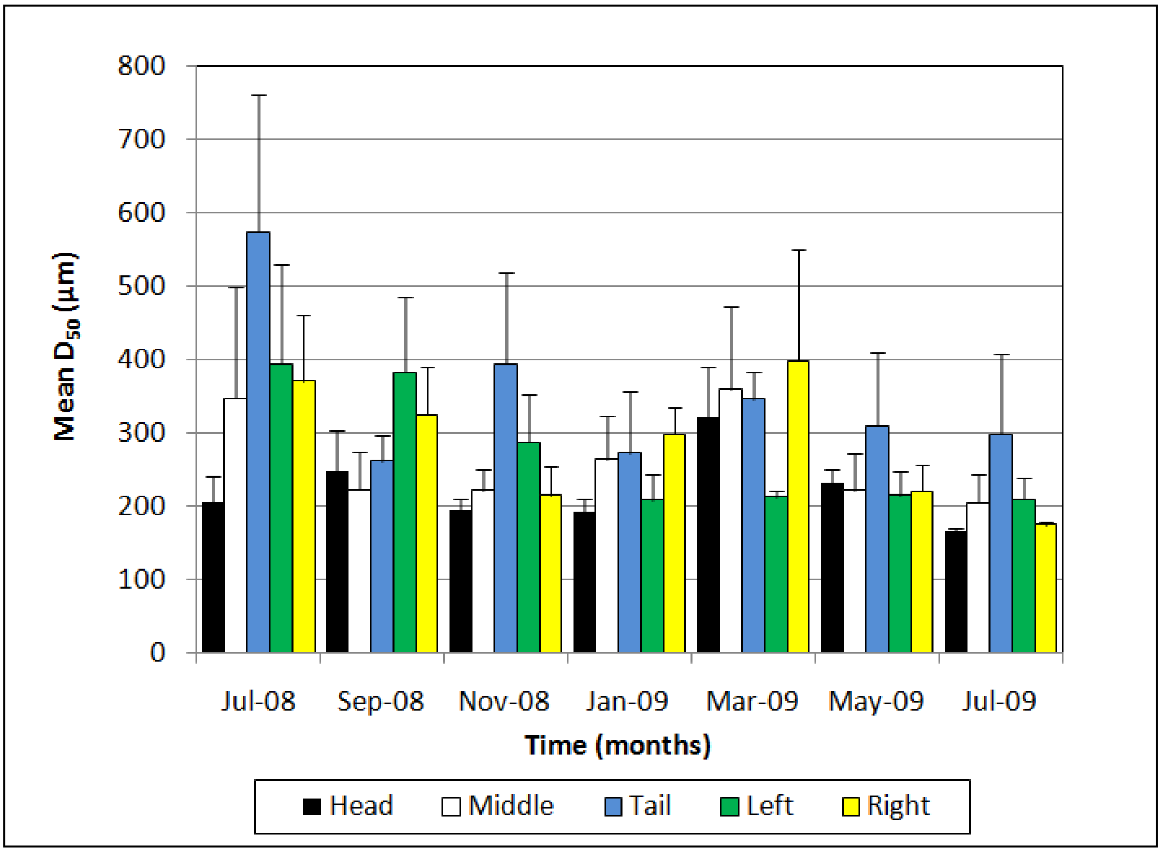


Figure 6.38 – Temporal differences in mean D_{50} of effective sediment between the five different zones investigated within *Ranunculus* patches on the River Frome at Frome Vauchurch between July 2008 and July 2009. The mean value is comprised from three values, each taken from the same corresponding zone within each of the three plants. The whiskers on the bars represent the standard error (SE).

months.

A further Kruskal-Wallis test was used to determine significant differences in D_{50} values between sample months using values from all three plants within each month. There was a highly significant difference (*d.f.* = 6, ***P*** <0.001) between all seven sample months for the values of D_{50} within the absolute sediment. The datasets were further treated with a series of *post-hoc* Mann-Whitney U-tests to reveal which sample months were significantly different to one another (Figure 6.39). The results from this analysis suggested that the D_{50} values for absolute sediment from July 2008 were significantly different to those from all of the other sample months with the exception of those from September 2008. Additionally, the D_{50} values from September 2008 were

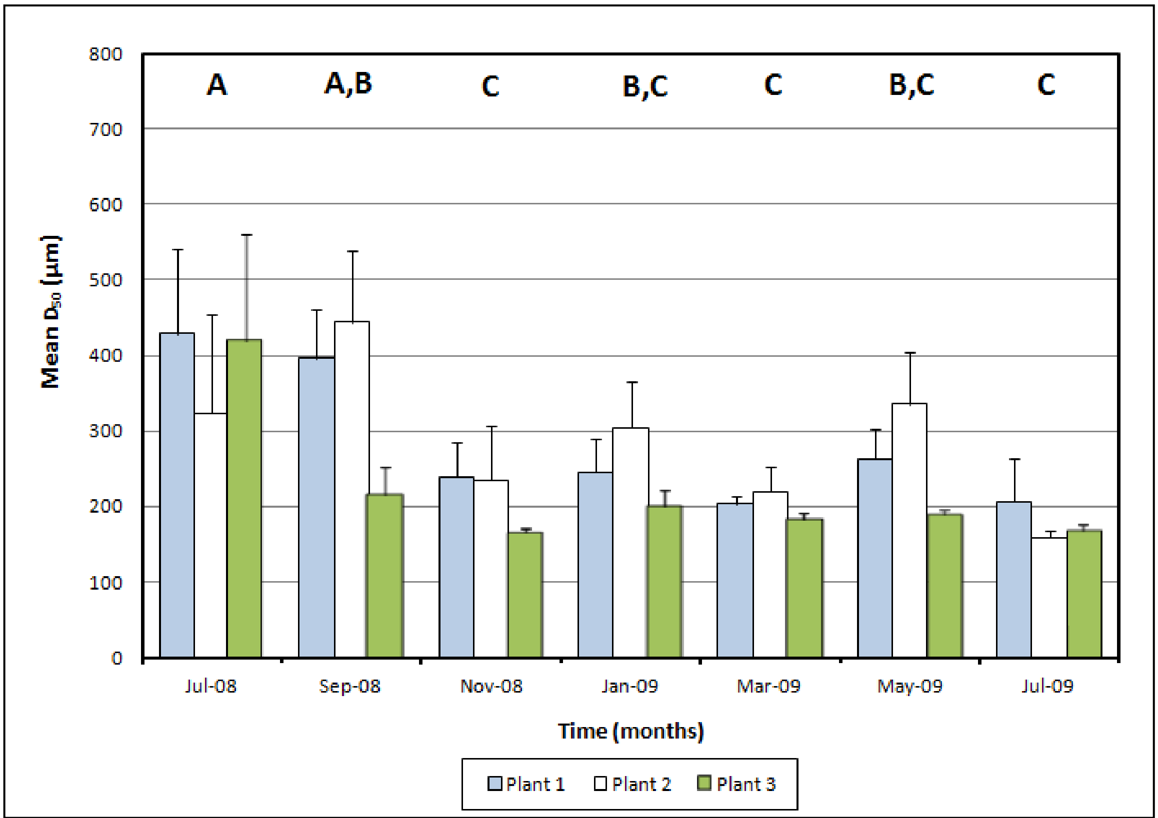


Figure 6.39 – The temporal changes in mean D_{50} of absolute fine sediment within all three *Ranunculus* plants between July 2008 and July 2009 on the River Frome at Frome Vauchurch. The whiskers on each bar indicate the standard error (SE). A ***P***-value is displayed within individual months where the three plants were statistically different for D_{50} values. The small-case letters within the bars indicate the results of *post-hoc* Mann-Whitney U-tests that determined which of the three plants are significantly different to one another. Bars with the same letters were determined to be not significantly different to one another (***P*** >0.05). The large capital letters above the bars indicate the results of a *post-hoc* Mann-Whitney U-tests that determined which months were significantly different to one another when D_{50} values from all three plants within each month were combined and the values were compared between months. Months with the same capital letter indicate that they are not significantly different from one another (***P*** >0.05).

significantly different to most of the other D_{50} values within the other sample months, with the exception of January 2009 and May 2009. All of the sample months from November 2008 to July 2009 were determined not to be significantly different from one another for values of D_{50}.

6.1.8.4 Changes in the absolute median particle size within different zones of *Ranunculus* on the River Frome

The variability of D_{50} values within absolute sediment samples was compared between the five zones within *Ranunculus* plants. The mean D_{50} value for each zone was calculated from the D_{50} values taken from the same corresponding zones within each of the three plants (Figure 6.40).

All zones with the exception of the head and tail zone had mean D_{50} values within the medium sand in the July 2008 sample month. The mean D_{50} value for the tail zone in July 2008 was the only zone within the coarse sand (500-1000 µm) during the entire one year period. During the one year survey period the head zone had consistently smaller mean D_{50} values in comparison with the other four zones. The mean D_{50} values within absolute sediment of the head zone were restricted to the fine sand (125-250 µm) in every sample month except in September 2008. In the September 2008 sample month all mean D_{50} values from the five zones were within the medium sand (250-500 µm). The mean D_{50} values of all of the zones except the tail zone were within the fine sand in the November 2008 and July 2009 sample months. In the January 2009 and May 2009 sample months mean D_{50} values of the five zones were between the fine and medium sand. But within the March 2009 sample month mean D_{50} values of all five zones were within the fine sand.

There appeared to be greater variability between D_{50} values within the majority of the five zones within July 2008 and September 2008 as demonstrated by the higher standard error values (Figure 6.40).

The greatest mean D_{50} value within the entire dataset was observed in the tail zone in July 2008 at 652 ± 201 (SE) µm, whilst the least was in the head zone in July 2009 at 149 ± 3 (SE) µm.

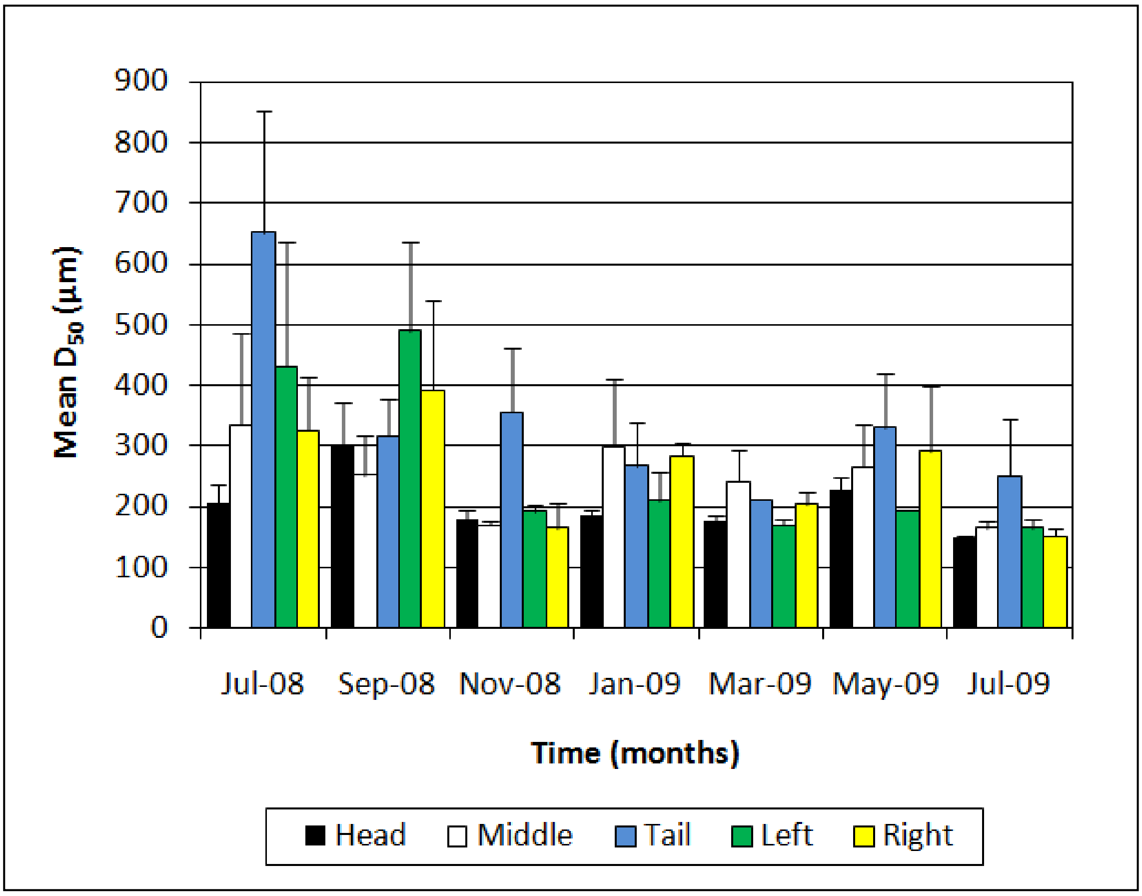


Figure 6.40 – Temporal differences in mean D_{50} of absolute sediment between the five different zones investigated within *Ranunculus* patches on the River Frome at Frome Vauchurch between July 2008 and July 2009. The mean value is comprised from three values, each taken from the same corresponding zone within each of the three plants. The whiskers on the bars represent the standard error (SE).

6.1.9 Variability in the % volume of silt and clay sized particles within *Ranunculus* plants on the River Frome

6.1.9.1 Changes in the mean % volume of silt and clay sized particles within the effective sediment between *Ranunculus* plants

Temporal variability in mean % volume of silt and clay sized particles (mean %SC hereafter) within effective sediment between the three *Ranunculus* plants are illustrated in Figure 6.41. Mean %SC values of effective sediment from all of the three plants ranged between 4.2 and 14.3 %. Values of mean %SC within plant two appeared to vary the least over time in comparison with the other three plants. The range, or difference between the greatest and least mean %SC within plant two was 3.8 %, in comparison with 7.4 and 9.4 % difference in the highest and least %SC values within plant one and three respectively. Mean values of %SC within plant one and three appeared to increase over time. The least mean value of %SC within plants one and three was in July 2008 and the greatest values for plant one and three appearing in the May 2009 and July 2009 correspondingly. In March 2009 the mean values of %SC within all three plants were notably lower in comparison with values in January 2009 and May 2009.

The greatest mean %SC value within the effective sediment was found in May 2009 within plant three (14.3 ± 0.8 (SE) %). Additionally, the least mean %SC value from plant three was determined in July 2008 (4.9 ± 0.5 (SE) %). Plant one had its greatest mean %SC value in July 2009 (11.7 ± 1.7 (SE) %), and its least mean %SC value in July 2008 at 4.2 ± 0.9 (SE) %. This was also the lowest mean %SC value between the three plants within the whole dataset. The greatest value of mean %SC within plant two occurred in July 2009 (10.2 ± 0.9 (SE) %), whilst the least value was in July 2008 (4.9 ± 0.5 (SE) %).

One-way ANOVA's were used to test the differences in %SC values between the three plants within each sampling month (Figure 6.41). The %SC values of the three plants were found to be significantly different in May 2009 only (*d.f.* = 2, ***P*** = 0.01). A *post-hoc* Fishers LSD test was conducted on the %SC values between the three plants in May 2009. The analysis revealed that values of %SC from plant one and two were not significantly different from one another. However, the %SC values from plant one and two were significantly different to those of plant three.

An additional one-way ANOVA was used to assess the significant differences in %SC values between sample months using values from all three plants within each month. There was a highly significant difference (*d.f. = 6*, ***P*** <0.001) between all seven sample months for the values of %SC within the effective sediment. The datasets were further treated with a Fishers LSD *post-hoc* test to reveal which sample months were significantly different to one another (Figure 6.41). The results from this analysis suggested that the %SC values for effective sediment from July 2008 were significantly different to the %SC values of all sample months except those from September 2008. In addition, %SC values from May 2009 and July 2009 were similar to one another, but statistically different to the %SC values from other sample months.

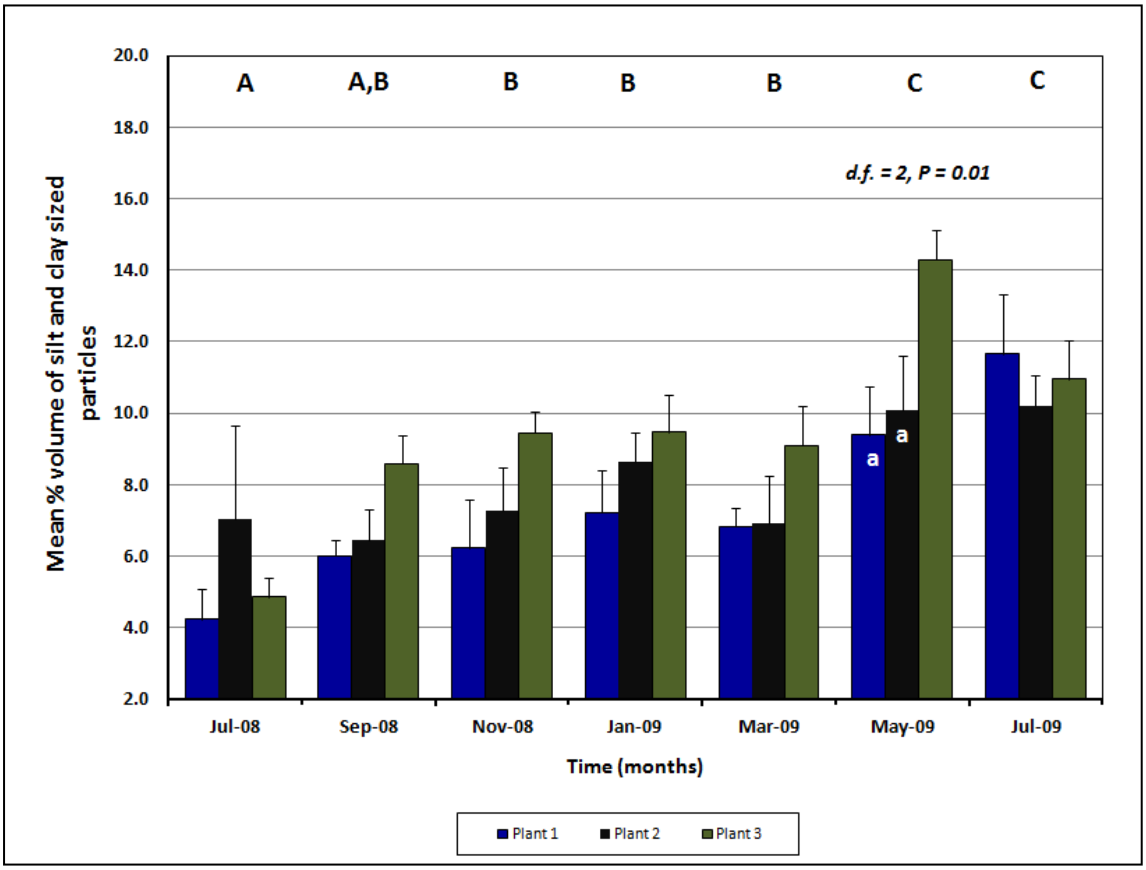


Figure 6.41 – The temporal changes in mean % volume of silt and clay sized particles (%SC) of effective fine sediment within all three *Ranunculus* plants between July 2008 and July 2009 on the River Frome at Frome Vauchurch. The whiskers on each bar indicate the standard error (SE). A ***P***-value is displayed within individual months where the three plants were statistically different for %SC values. The small-case letters within the bars indicate the results of a *post-hoc* Fishers LSD test that determined which of the three plants are significantly different to one another. Bars with the same letters were determined to be not significantly different to one another (***P*** >0.05). The large capital letters above the bars indicate the results of a *post-hoc* Fishers LSD test that determined which months were significantly different to one another when %SC values from all three plants within each month were combined and the values were compared between months. Months with the same capital letter indicate that they are not significantly different from one another (***P*** >0.05).

6.1.9.2 Spatial and temporal differences in % volume of silt and clay-sized particles of effective sediment within *Ranunculus* plants

The variability of %SC within effective sediment samples was compared between the five zones within the *Ranunculus* plants. The mean %SC value for each zone was calculated from the %SC values taken from the same corresponding zone within each of the three plants (Figure 6.42).

Values of mean %SC within the entire one year dataset varied between 2.9 and 13.7 %. The tail, left and right lateral zone in July 2008 possessed the least values of mean %SC within the whole dataset. The least value of mean %SC was observed in the tail zone in July 2008 at 3.0 ± 0.8 (SE) %. The greatest mean %SC values of effective sediment within each zone were observed in the May 2009 and July 2009 sample months. Mean %SC values of all zones were >10 % in May 2009 and July 2009 with

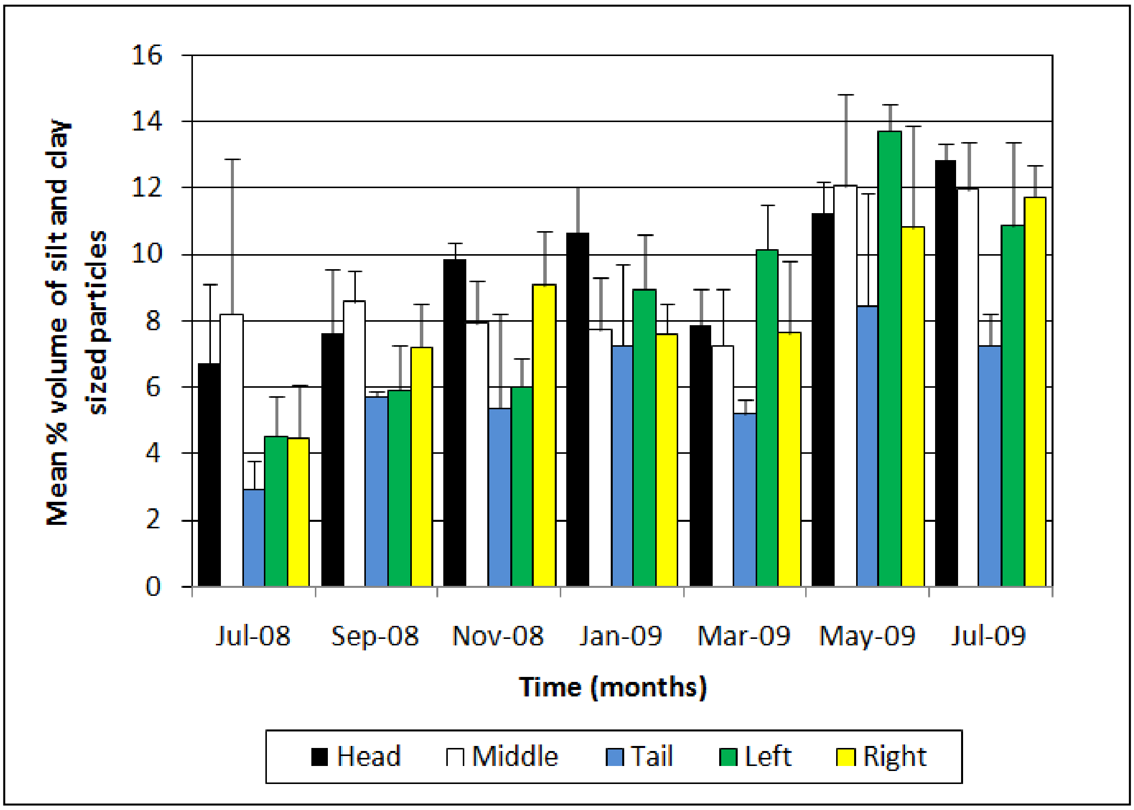


Figure 6.42 – Temporal differences in mean % volume of silt and clay sized particles (%SC) within the effective sediment from the five different zones investigated within *Ranunculus* patches on the River Frome at Frome Vauchurch between July 2008 and July 2009. The mean value is comprised from three values, each taken from the same corresponding zone within each of the three plants. The whiskers on the bars represent the standard error (SE).

the exception of the tail zone which was always <9.0 %. The left lateral zone possessed the greatest values of mean %SC in May 2009 of 13.7 ± 0.8 (SE) %.

The values of mean %SC in the head, middle and tail zone were conspicuously lower in March 2009 in comparison with the %SC values for those zones in January 2009 and May 2009. There appeared to be a general increase in the values of mean %SC within the head, tail and right lateral zone between July 2008 and May 2009. The tail zone noticeably possessed the least mean %SC values within each sample month.

6.1.9.3 Changes in the mean % volume of silt and clay sized particles within the absolute sediment fraction between *Ranunculus* plants

Temporal variability in mean %SC values within absolute sediment between the three *Ranunculus* plants are illustrated in Figure 6.43. Mean %SC values of absolute sediment from all of the three plants ranged between 2.9 and 13.7 %. In general all three plants had comparable values of mean %SC within each sample month except plant two in July 2008 and November 2008, where mean %SC values were noticeably greater than those from plant one and three. All three plants had comparable mean %SC values that were <10 % between July 2008 and May 2009 with the exception of plant two in November 2008. All three plants had conspicuously greater values of mean %SC in July 2009 in comparison with the mean %SC values from the previous months.

The greatest mean %SC value within the absolute sediment was from plant two in November 2008 (13.7 ± 6.9 (SE) %). The least mean %SC value from plant three was determined in September 2008 (6.2 ± 1.7 (SE) %). Plant one had its greatest mean %SC in March 2009 (13.4 ± 2.3 (SE) %), and its least mean %SC value in the July 2008 sample month at 2.9 ±1.0 (SE) %. This was also the lowest mean %SC value between the three plants within the whole dataset. The greatest value of mean %SC within plant three occurred in July 2009 (13.1 ± 2.5 (SE) %), whilst the least value was in July 2008 (4.7 ± 0.6 (SE) %).

One-way ANOVA's were used to test the differences in %SC values between the three plants within each sampling month (Figure 6.43). No significant differences were found in the %SC values of the three plants within any of the seven sample months.

An additional one-way ANOVA was used to test for significant differences in %SC values between sample months using values from all three plants within each month. There was a significant difference (*d.f.* = *6*, ***P*** = 0.01) between all seven sample months for the values of %SC within the absolute sediment. The datasets were further treated with a Fishers LSD *post-hoc* test to reveal which sample months were significantly different to one another (Figure 6.43). The results from this analysis suggested that the %SC values for absolute sediment from July 2008 were significantly

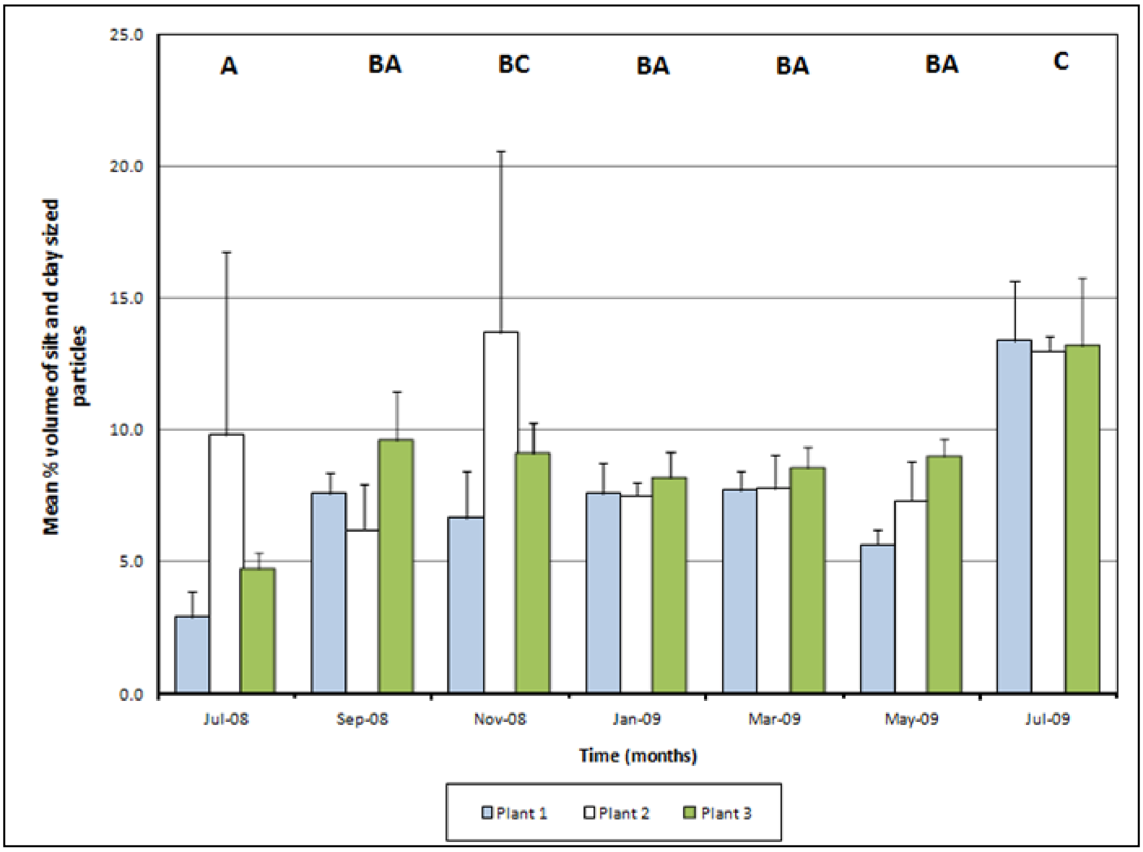


Figure 6.43 – The temporal changes in mean % volume of silt and clay sized particles (%SC) from absolute fine sediment within all three *Ranunculus* plants between July 2008 and July 2009 on the River Frome at Frome Vauchurch. The whiskers on each bar indicate the standard error (SE). A ***P***-value is displayed within individual months where the three plants were statistically different for %SC values. The small-case letters within the bars indicate the results of a *post-hoc* Fishers LSD test that determined which of the three plants are significantly different to one another. Bars with the same letters were determined to be not significantly different to one another (***P*** >0.05). The large capital letters above the bars indicate the results of a *post-hoc* Fishers LSD test that determined which months were significantly different to one another when %SC values from all three plants within each month were combined and the values were compared between months. Months with the same capital letter indicate that they are not significantly different from one another (***P*** >0.05).

different to values from November 2008 and July 2009. Furthermore, %SC values from July 2009 were significantly different to values from all of the other months, with the exception of November 2009.

6.1.9.4 Spatial and temporal differences in % volume of silt and clay-sized particles of the absolute sediment fraction within *Ranunculus* plants

The variability of %SC within absolute sediment samples was compared between the five zones within *Ranunculus* plants. The mean %SC value for each zone was calculated from the %SC values taken from the same corresponding zones within each of the three plants (Figure 6.44).

Values of mean %SC within the entire one year dataset ranged between 1.5 and 17.6 %. The majority of all five zones appeared to possess comparatively similar mean %SC values that were between 5 and 10 % from July 2008 to May 2009. The tail, left and right lateral zones possessed the least values of mean %SC within the whole dataset at 1.5, 3.3 and 3.3 % respectively within the July 2008 sample month. Additionally, the mean %SC value of the middle zone in July 2008 and the right lateral zone in November 2008 were considerably greater, and both possessed higher standard error values. The right lateral zone in November had the greatest mean %SC value in the dataset at 17.6 ± 14.1 (SE) %. Furthermore, all zones except the tail zone were notably greater than 10 % in the July 2009 survey month. The tail zone possessed the least value of mean %SC within each sample month.

6.1.10 Variability in particle sorting values within *Ranunculus* plants on the River Frome

The Trask sediment sorting coefficient (S_0) (Trask, 1932) was used to analyse the extent of sediment sorting within effective and absolute sediment samples from *Ranunculus* plants on the River Frome at Frome Vauchurch.

6.1.10.1 Changes in particle sorting within the effective sediment fraction between *Ranunculus* plants

Variations in the mean S_0 values of effective sediment between the three *Ranunculus* plants over the one year survey period are illustrated in Figure 6.45. Mean S_0 values of effective sediment from all of the three plants ranged from 0.43 to 0.67. The effective sediment samples from plant three had the greatest mean S_0 values in all sample months. The mean S_0 values from plant three were much greater than the mean S_0 values from plant one, but they shared a similar pattern of mean S_0 values over the one year

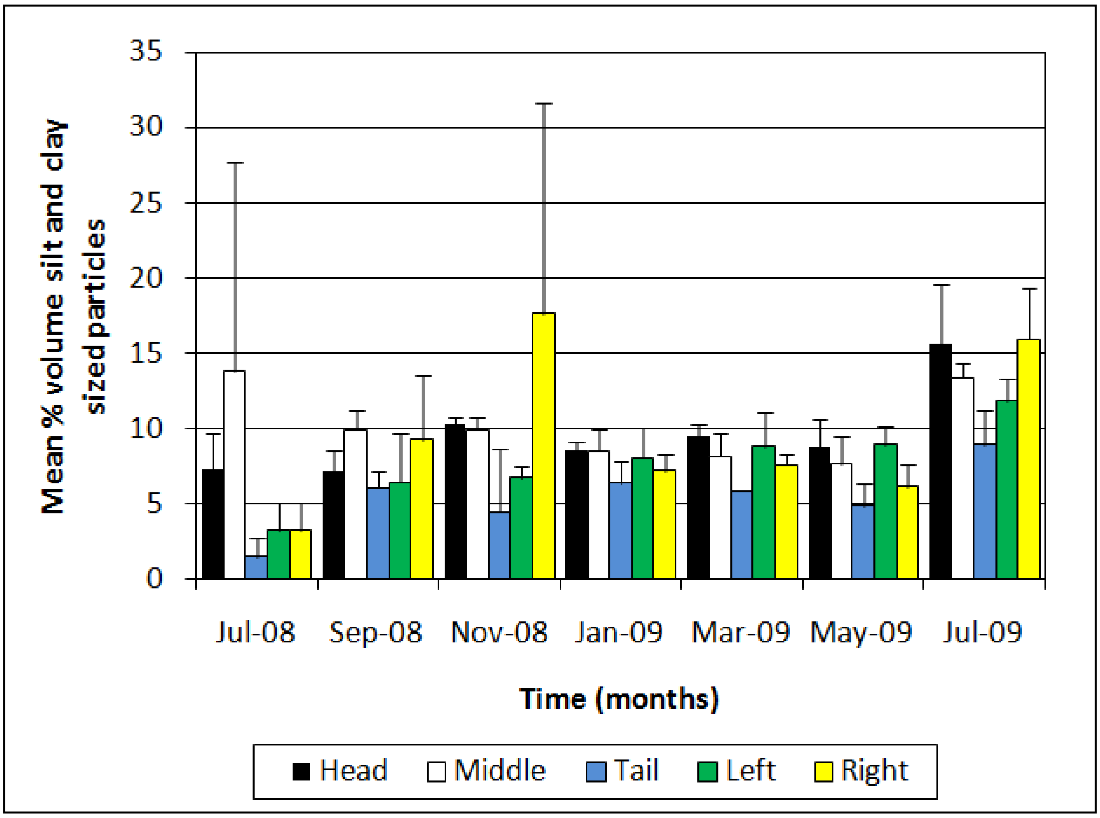


Figure 6.44 – Temporal differences in mean % volume of silt and clay sized particles (%SC) within the absolute sediment from the five different zones investigated within *Ranunculus* patches on the River Frome at Frome Vauchurch between July 2008 and July 2009. The mean value is comprised from three values, each taken from the same corresponding zone within each of the three plants. The whiskers on the bars represent the standard error (SE).

period. Plant two had considerably smaller mean S_0 values compared with those from plant one and three, with the exclusion of the September 2008 sample month where the value of mean S_0 within plant two was greater than plant one.

The greatest mean S_0 value within the effective sediment was found in July 2009 within plant three (S_0 0.67 ± 0.02 (SE)), and the least mean S_0 value from plant three was determined in May 2009 (S_0 0.57 ± 0.02 (SE)). The greatest mean S_0 from plant one occurred in July 2009 (S_0 0.65 ± 0.03 (SE)), and the least mean S_0 value from plant one was in the September 2008 sample month at S_0 0.51 ± 0.02 (SE). The greatest value of mean S_0 within plant two occurred in July 2009 (S_0 0.58 ± 0.05 (SE)), whilst its

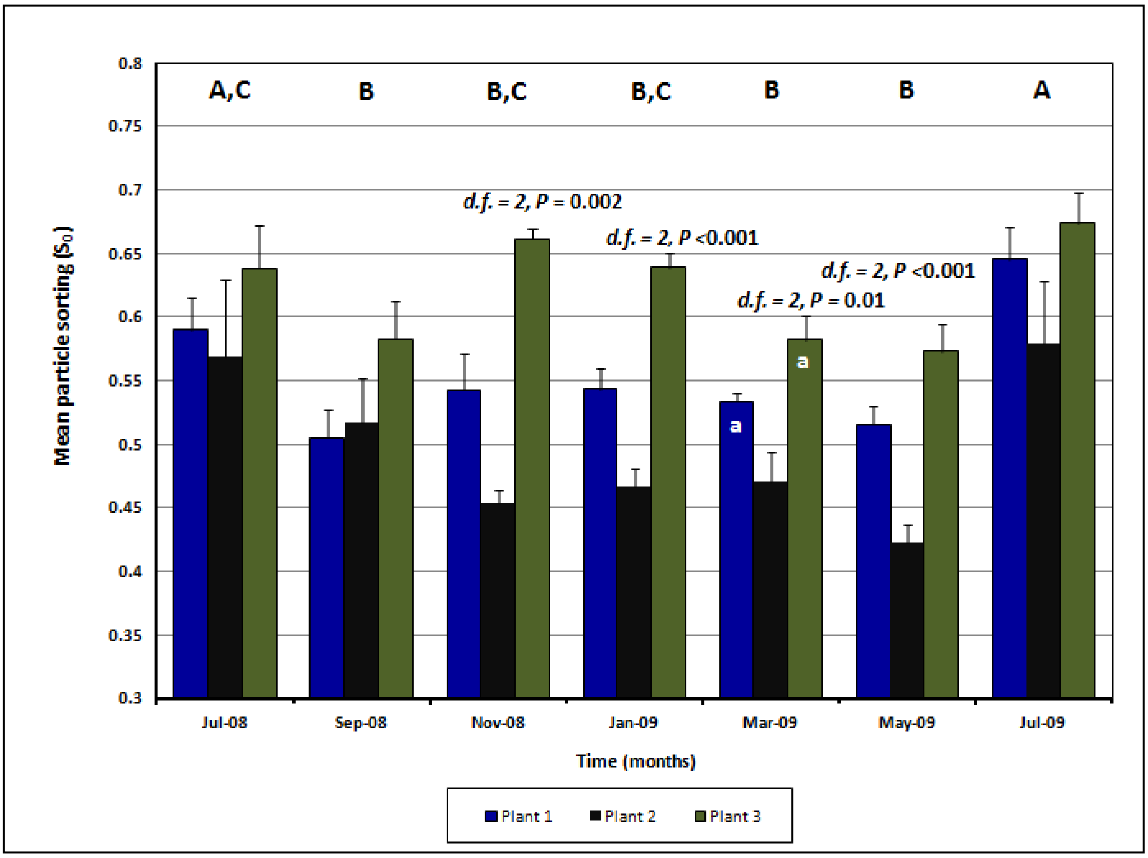


Figure 6.45 – The temporal changes in mean particle sorting (S_0) of effective fine sediment within all three *Ranunculus* plants between July 2008 and July 2009 on the River Frome at Frome Vauchurch. The whiskers on each bar indicate the standard error (SE). A ***P***-value is displayed within individual months where the three plants were statistically different for S_0 values. The small-case letters within the bars indicate the results of a *post-hoc* Fishers LSD test that determined which of the three plants are significantly different to one another. Bars with the same letters were determined to be not significantly different to one another (***P*** >0.05). The large capital letters above the bars indicate the results of a *post-hoc* Fishers LSD test that determined which months were significantly different to one another when S_0 values from all three plants within each month were combined and the values were compared between months. Months with the same capital letter indicate that they are not significantly different from one another (***P*** >0.05).

least value was in May 2009 (S_0 0.42 ± 0.02 (SE)). Additionally, this was also the smallest mean S_0 value within the entire dataset.

One-way ANOVA's were used to test the differences in S_0 values between the three plants within each sampling month (Figure 6.45). The S_0 values of the three plants were found to be significantly different to one another in November 2008, January 2009, March 2009 and May 2009 at *d.f.* = 2, ***P*** = 0.002; *d.f.* = 2, ***P*** <0.001; *d.f.* = 2, ***P*** = 0.01 and *d.f.* = 2, ***P*** <0.001 correspondingly. A series of *post-hoc* Fishers LSD tests were conducted on the S_0 values between the three plants in November 2008, January 2009, March 2009 and May 2009. The result of the HSD analysis in November 2008, January 2009 and May 2009 determined that all three plants were significantly different to one another regarding their S_0 values. In March 2009 values of S_0 were found not to be significantly different between plant one and plant three, whilst values from plant two were significantly different to those from both plant one and three.

A further one-way ANOVA was used to test for significant differences in S_0 values between sample months using values from all three plants within each month. There was a highly significant difference (*d.f.* = *6*, ***P*** <0.001) between all seven sample months for the values of S_0 within the effective sediment. The datasets were further treated with Fishers LSD *post-hoc* test to reveal which sample months were significantly different to one another (Figure 6.45). The results from this analysis suggested that the S_0 values for effective sediment from July 2009 were significantly different to values from all sample months except July 2008. Additionally, the S_0 values from July 2008 were statistically different to those from other months except November 2008 and January 2009.

6.1.10.2 Spatial and temporal differences in particle sorting within the effective sediment fraction inside *Ranunculus* plants

The variability of S_0 values within effective sediment samples was compared between the five zones found within *Ranunculus* plants. The mean S_0 value for each zone was calculated from the S_0 values taken from the same corresponding zones within each of the three plants (Figure 6.46). Mean S_0 values within the entire dataset were between 0.47 and 0.69. All five zones within each sampling month between September 2008 and May 2009 appeared to have similar mean S_0 values and values of standard error, with mean S_0 values between 0.47 and 0.59. Within the July 2008 survey month the head and tail zones possessed greater values of mean S_0 at 0.63 and 0.69 respectively. In the July 2009 sample month all zones had mean S_0 values greater than 0.60, with the exception of the middle zone. The head zone in the May 2009 sample month had the least mean S_0 value (S_0 0.47 ± 0.04 (SE)), and the tail zone in the July 2008 sample month had the greatest value (S_0 0.69 ± 0.03 (SE)). There were no conspicuous temporal patterns present in the mean S_0 values from each zone.

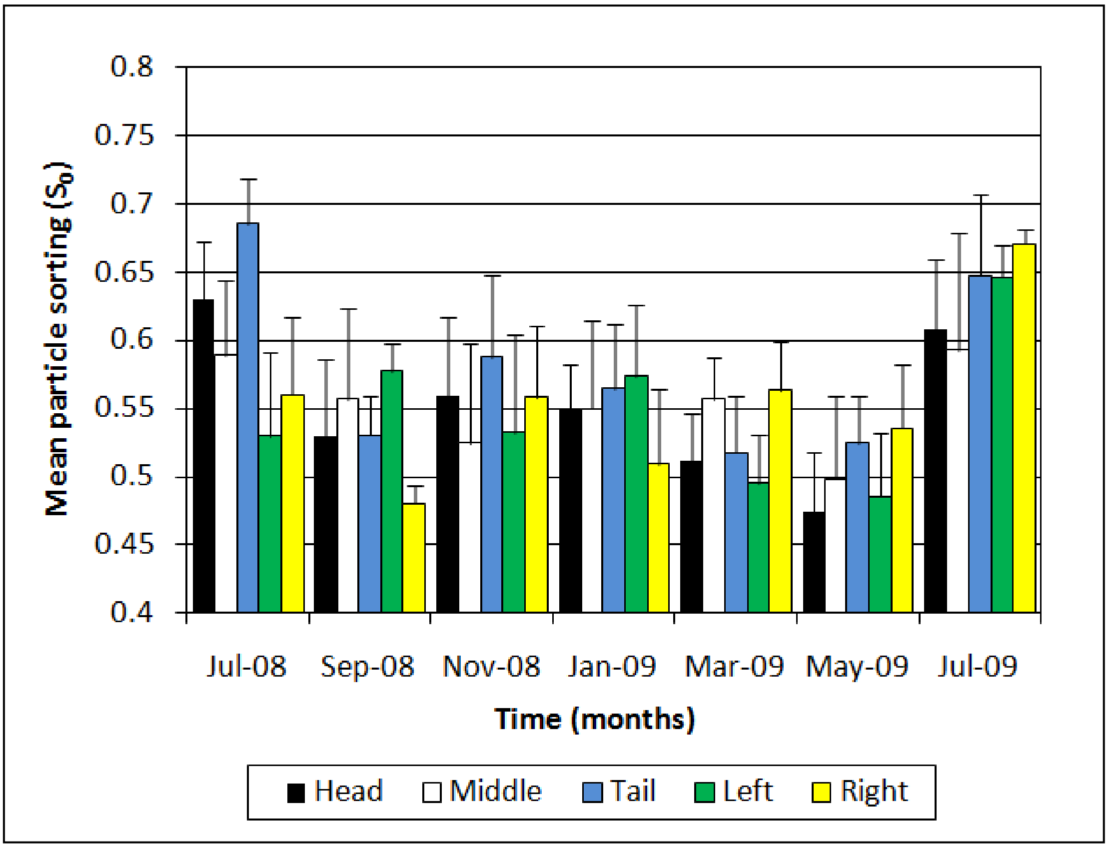


Figure 6.46 – Temporal differences in mean particle sorting (S_0) within the effective sediment from the five different zones investigated within *Ranunculus* patches on the River Frome at Frome Vauchurch between July 2008 and July 2009. The mean value is comprised from three values, each taken from the same corresponding zone within each of the three plants. The whiskers on the bars represent the standard error (SE).

6.1.10.3 Changes in particle sorting within the absolute sediment fraction between *Ranunculus* plants

Variations in mean S_0 values of absolute sediment between the three *Ranunculus* plants over the one year survey period are illustrated in Figure 6.47. Mean S_0 values of absolute sediment from all of the three plants ranged from 0.46 to 0.72.

There were no prominent seasonal patterns in the values of mean S_0 within any of the three plants, and all three plants had dissimilar increases and decreases in mean S_0 values throughout the one year period. However the mean S_0 values from plant three were the greatest in each sample month, whilst the mean S_0 values from plant two were the least in all months except those from September 2008. The greatest mean S_0 value within the absolute sediment was found in November 2008 within plant three (S_0 0.72 ± 0.01 (SE)). The least mean S_0 value from plant three was determined in July 2009 (S_0 0.61 ± 0.02 (SE)). The greatest mean S_0 value from plant one occurred in July 2008 (S_0 0.64 ± 0.03 (SE)), and the least mean S_0 value from plant one was in the September 2008 sample month at S_0 0.50 ± 0.02 (SE). The greatest value of mean S_0 within plant two occurred in July 2008 (S_0 0.57 ± 0.11 (SE)), whilst the least value was in September 2008 (S_0 0.46 ± 0.02 (SE)).

A one-way ANOVA was used to test for significant differences in S_0 values between the three plants within each sample month. Significant differences in S_0 values were found between the three plants in all of the sample months except July 2008 and September 2008 (Figure 6.47). The S_0 values of all three plants were significantly different to each other in the November 2008, January 2009 and May 2009 sample months. Within the March 2009 and July 2009 sample months there was no significant difference found between plant one and three regarding values of S_0, however they were significantly different to the S_0 values of samples from plant two within both months.

A further one-way ANOVA was used to test for significant differences in S_0 values between sample months using values from all three plants within each month. There were no significant differences (*d.f.* = *6*, ***P*** >0.05) found between any of the months for values of S_0 within absolute sediment samples.

6.1.10.4 Spatial and temporal differences in particle sorting within the absolute sediment fraction inside *Ranunculus* plants

The variability of S_0 values within the absolute sediment samples was compared between the five zones identified within *Ranunculus* plants. The mean S_0 value for each zone was calculated from the S_0 values taken from the same corresponding zones within each of the three plants (Figure 6.48).

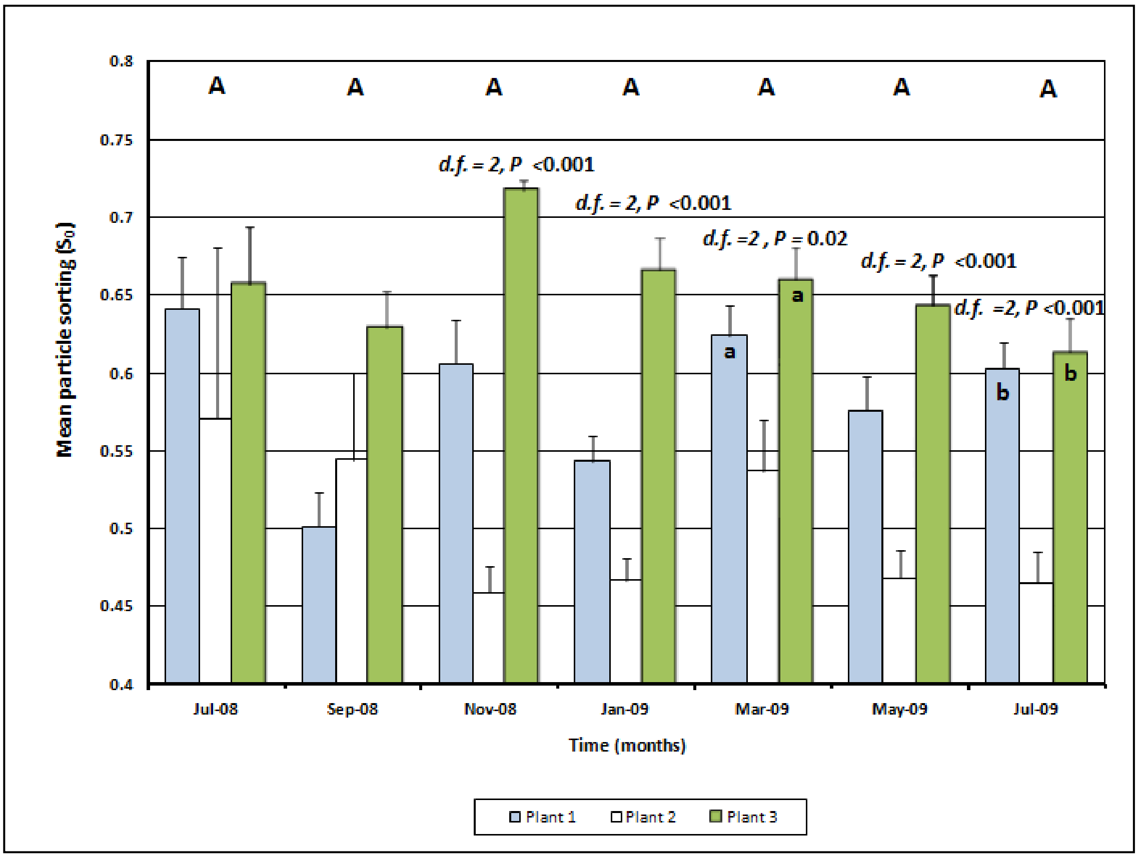


Figure 6.47 – The temporal changes in mean particle sorting (S_0) of absolute fine sediment within the three *Ranunculus* plants between July 2008 and July 2009 on the River Frome at Frome Vauchurch. The whiskers on each bar indicate the standard error (SE). A ***P***-value is displayed within individual months where the three plants were statistically different for S_0 values. The small-case letters within the bars indicate the results of a *post-hoc* Fishers LSD test that determined which of the three plants are significantly different to one another. Bars with the same letters were determined to be not significantly different to one another (***P*** >0.05). The large capital letters above the bars indicate which months were significantly different to one another when S_0 values from all three plants within each month were combined and the values were compared between months. Months with the same capital letter indicate that they are not significantly different from one another (***P*** >0.05).

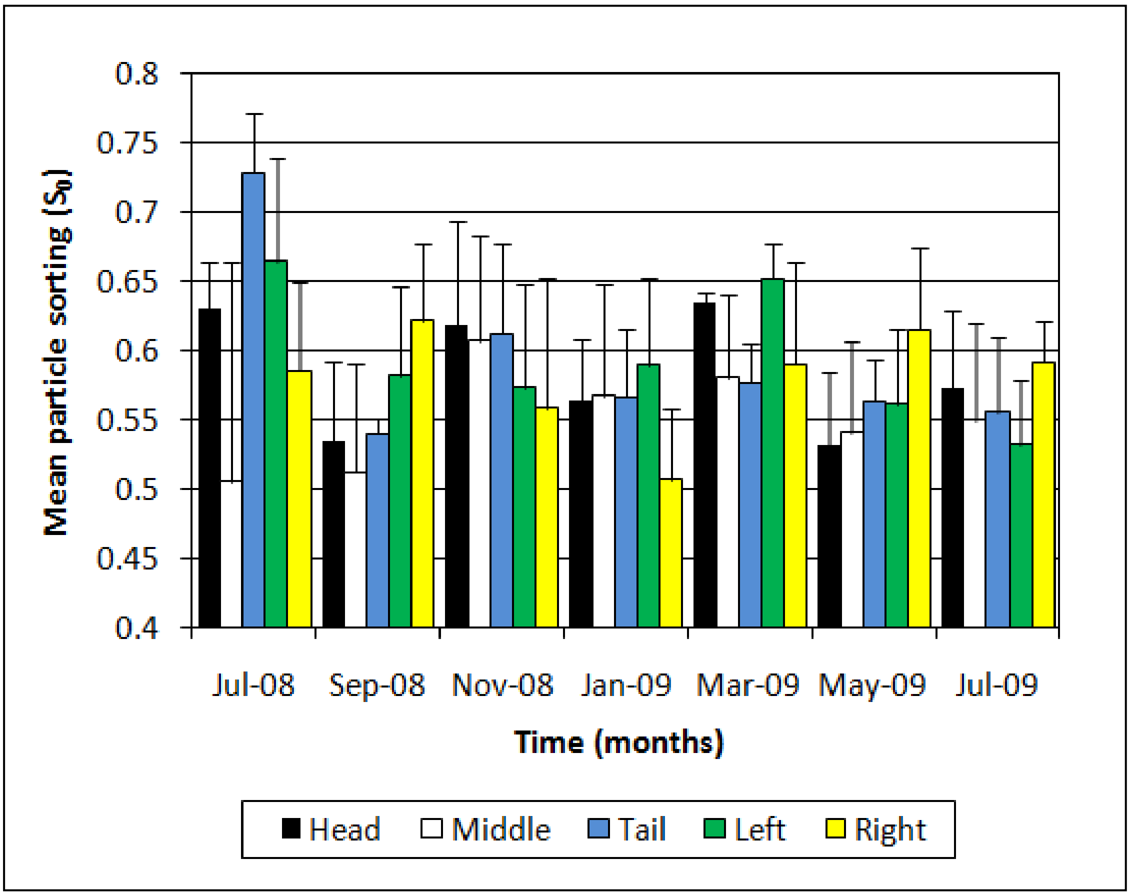


Figure 6.48 – Temporal differences in mean particle sorting (S_0) within the absolute sediment from the five different zones investigated within *Ranunculus* patches on the River Frome at Frome Vauchurch between July 2008 and July 2009. The mean value is comprised from three values, each taken from the same corresponding zone within each of the three plants. The whiskers on the bars represent the standard error (SE).

All zones possessed similar mean S_0 values and associated values of standard error throughout the one year sampling period. The majority of the five zones within each sampling month possessed mean S_0 values between 0.50 and 0.60. The head, tail and left lateral zone within July 2008 had mean S_0 values that were noticeably greater than 0.60, these were 0.63, 0.73, 0.66 correspondingly. The tail zone possessed the greatest mean S_0 value within the entire dataset (S_0 0.73 ± 0.04 (SE)). The head and left lateral zone within the March 2009 sampling month also appeared to have greater mean S_0 values compared to the rest of the zones in the entire dataset. Additionally, the middle zone in July 2008 had the least mean S_0 value within the one year dataset (S_0 0.50 ± 0.16 (SE)) and the greatest standard error value.

6.1.11 Variability in the organic matter content within *Ranunculus* plants on the River Frome

6.1.11.1 Changes in the % organic matter of sediment between *Ranunculus* plants

The variability of mean % organic matter content (%OM hereafter) between the three *Ranunculus* plants over the one year survey period are illustrated in Figure 6.49. Mean %OM values of sediment from all of the three plants ranged from 1.4 to 6.0 %, with most mean %OM values being <4 %. Within all sample months except July 2008 plant three had the greatest mean %OM values, whilst the lowest mean %OM values were within plants one and two. The mean %OM values of all three plants appeared to be lower in January 2009 and March 2009 in comparison with other months in the one year period.

The greatest mean %OM value was determined in July 2008 within plant two (6.0 ± 2.9 (SE) %). The least mean %OM value from plant two was determined in March 2009 as 1.4 ± 0.3 (SE) %. Plant one had its greatest mean %OM in July 2008 (2.7 ± 0.6 (SE) %), and the least mean %OM value in March 2009 at 1.4 ± 0.1 (SE) %. The mean values of %OM in plant one appeared to show less variation throughout the seven month sampling period in comparison with corresponding values from plant two and three. The greatest mean %OM within plant three occurred in May 2009 (3.6 ± 0.8 (SE) %), whilst the least mean %OM value was in January 2009 (1.8 ± 0.2 (SE) %).

A series of Kruskal-Wallis analyses were used to test the differences in %OM values between the three plants within each sampling month (Figure 6.49). The %OM values of the three plants were found to be significantly different in November 2008 and May 2009 at *d.f* = 2, ***P*** = 0.001 and *d.f* = 2, ***P*** = 0.01 respectively. A series of *post-hoc* Mann-Whitney U-tests were conducted on the %OM values between the three plants in November 2008 and May 2009. Within the November 2008 sample month the %OM values from plant two and three were determined as not significantly different from one another, but the %OM values from plant two and three were determined to be significantly different to those of plant one. In May 2009 the %OM values from plant one and two were not significantly different from one another. But values of %OM from plant one and two were significantly different to those from plant three.

A further Kruskal-Wallis analysis was used to test for significant differences in %OM values between sample months using values from all three plants within each month. There were no significant differences (*d.f.* = *6*, ***P*** >0.05) found between the seven survey months for %OM values.

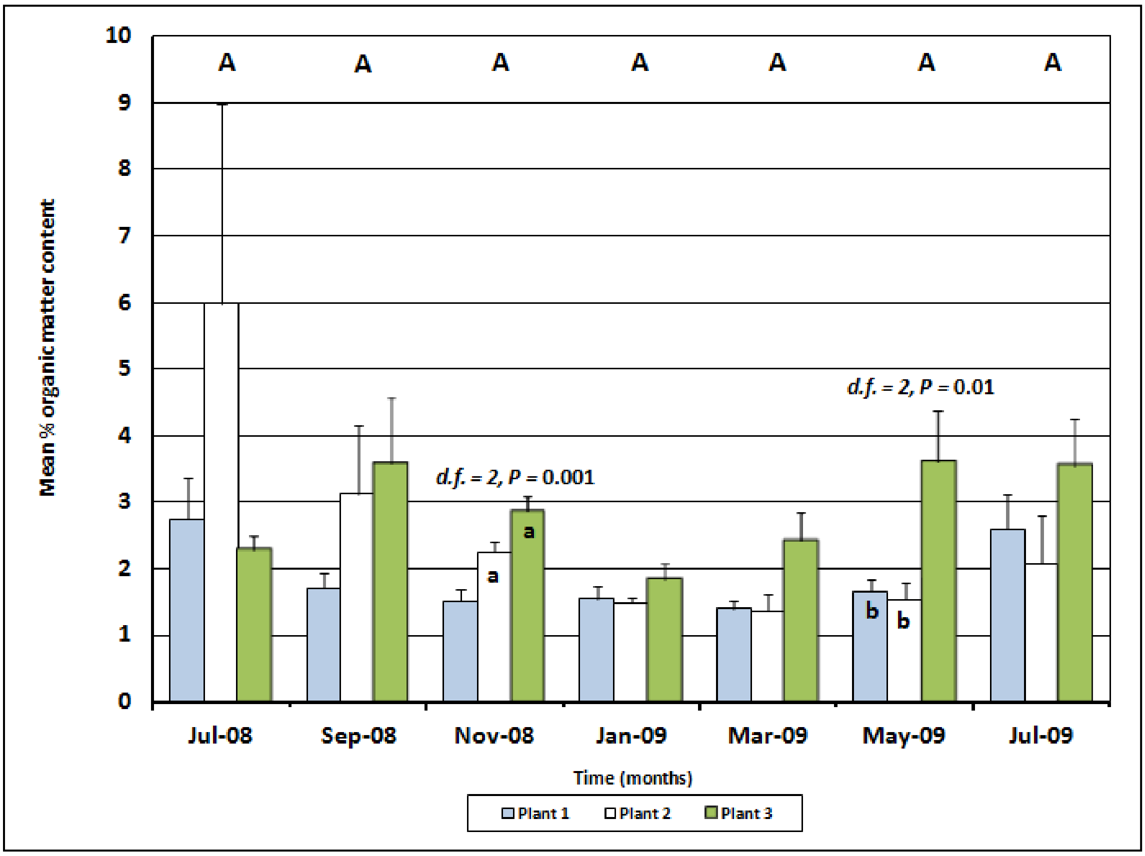


Figure 6.49 – The temporal changes in mean % organic matter (%OM) of fine sediment within the three *Ranunculus* plants between July 2008 and July 2009 on the River Frome at Frome Vauchurch. The whiskers on each bar indicate the standard error (SE). A ***P***-value is displayed within individual months where the three plants were statistically different for %OM values. The small-case letters within the bars indicate the results of *post-hoc* Mann-Whitney U-tests that determined which of the three plants are significantly different to one another. Bars with the same letters were determined to be not significantly different to one another (***P*** >0.05). The large capital letters above the bars indicate which months were significantly different to one another when %OM values from all three plants within each month were combined and the values were compared between months. Months with the same capital letter indicate that they are not significantly different from one another (***P*** >0.05).

6.1.11.2 Spatial and temporal differences in the % organic matter of sediment within *Ranunculus* plants

The variability of %OM values within the sediment samples were compared between the five zones within *Ranunculus* plants. The mean %OM value for each zone was calculated from the inclusion of %OM values taken from the same corresponding zones within each of the three plants (Figure 6.50).

In general, all five zones appeared to have similar mean %OM values and associated standard error throughout the one year sampling period, with the majority of mean %OM values between 3 and 4 %. The right lateral zone within the July 2008 and September 2008 sample months had conspicuously high mean %OM values, with the greatest value of mean %OM being in the July 2008 sample month at 7.8 ± 5.0 (SE) %.

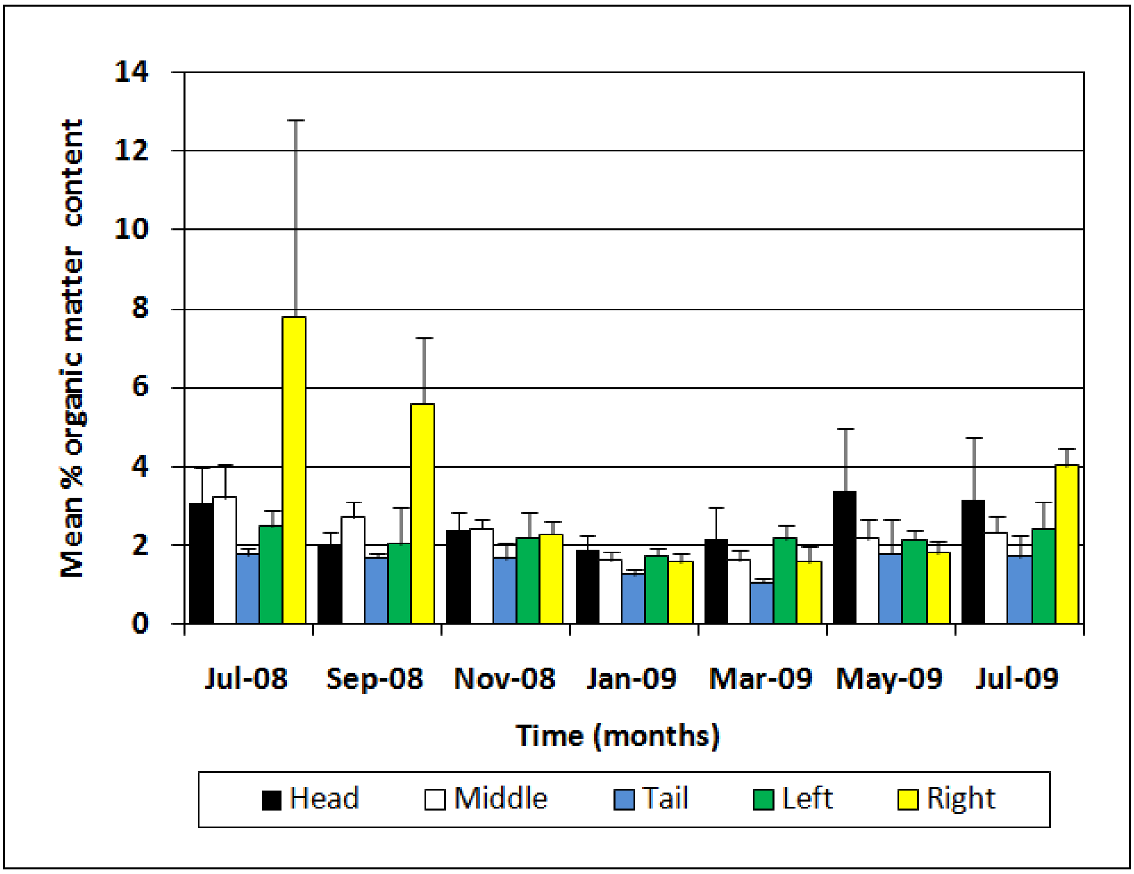


Figure 6.50 – Temporal differences in mean % organic matter content (%OM) within the sediment from the five different zones investigated within *Ranunculus* patches on the River Frome at Frome Vauchurch between July 2008 and July 2009. The mean value is comprised from three values, each taken from the same corresponding zone within each of the three plants. The whiskers on the bars represent the standard error (SE).

The zone with the least value of mean %OM was the tail zone in the March 2009 sample month at 1.1 ± 0.1 (SE) %. Additionally, the tail zone had the least value of mean %OM within all seven sample months.

6.2 Discussion

6.2.1 Seasonal changes of fine sediment volume and deposition within plant patches

The *Ranunculus* patches on the Bere Stream followed a similar pattern of seasonal growth and abundance. Bere Stream plants were similar in area and shape throughout the measurement period, with the peak in areal cover being in March 2009 or May 2009. In comparison, the *Ranunculus* patches on the River Frome did not have clear seasonal patterns in their growth cycle, albeit maximum growth was still between March 2009 and July 2009.

The *Ranunculus* patches also possessed significant R^2 values for the relationship between the area of their rooted section and the total plant area cover. This differed greatly with the plants observed on the River Frome due to the limited seasonal growth patterns of the plant and rooted area. *Ranunculus* patches at the River Frome were generally larger than those on the Bere Stream throughout the measurement period, as indicated by the mean areal cover. There was very little difference in patch shape between the three plants at the River Frome although there was considerable difference in plant rooted area, with only two plants possessing significant R^2 values for the relationship between the total area of plants and the rooted area of plants. A low R^2 value was determined when data from all three plants were combined together for the relationship between the total are of plants and their rooted areas.

The difference in seasonal patch size and morphology was possibly a reflection of the variations in hydrological conditions at each site (Gurnell *et al*., 2010; Haslam, 1987). *Ranunculus* patches on the Frome appeared to reach an optimum areal cover after which there were minor changes in total areal cover over time. Patches generally remained long and thin, which may have been the result of plant reconfiguration to decrease the impact of drag forces on the plants (Green, 2005a; O'Hare *et al*., 2007a; Sand-Jensen, 2003; Sand-Jensen and Pedersen, 1999; Statzner *et al*., 2006). The three

Ranunculus observed on the Bere Stream also reverted to the long and thin morphology in July 2008 and in the over-winter period. This suggests that patches of *R. penicillatus subsp. pseudofluitans* on the River Frome may be ecotypes or morphotypes (Gurnell *et al*., 2010) that are adapted to the highly variable nature of discharge, associated flow velocities and drag within the channel (Vogel, 1984; Vogel, 1994). This is consistent with the observations of another previous study that termed this response to hydrological conditions as a phenotype-driven morphological adaptation called 'plasticity' (Garbey *et al*., 2006). In contrast, *R. penicillatus subsp. pseudofluitans* patches on the Bere Stream appeared to survive the over-winter period with seasonally higher discharge. This contrasts with the previous study by Butcher (1933) who suggested that patches are commonly 'washed-out' by increases in winter channel discharge.

It was observed in this current study that reach-scale *Ranunculus* areal cover decreased dramatically with increases in seasonal discharge at both the River Frome and on the Bere Stream. Both sites possess different hydrological regimes (*c.f.* Figures 4.28 & 4.29 in section 4.1.8), therefore the seasonal variations in total plant cover (*c.f.* Figures 6.1 & 6.12) may suggest that the *Ranunculus* patches on the Bere Stream are not well adapted to cope with rapid changes in discharge in comparison with those on the River Frome. The total areal of all three *Ranunculus* plants on the Bere Stream were found to proportionally increase with increasing seasonal discharge, with the peak of mean total area for all three plants coinciding with the peak in discharge during the March 2009 survey. While the area of the three plants on the River Frome were found not to follow seasonal changes in channel discharge. This is also reflected in the seasonal variations of rooted area within the patches. It could be suggested that the high association with plant rooted area and total plant area in the Bere Stream is an indication that the plants were able to regulate their rooting area to provide optimum anchorage throughout the seasonal period. In contrast, *Ranunculus* plants on the River Frome maintained similar rooted areas throughout the survey period, which was probably an adaptation to counteract the flashy hydrological regime present at the site.

Within all three *Ranunculus* patches at both sites the composite volume possessed a robust linear relationship with corresponding total area cover values. This suggested that the area of *Ranunculus* plants is a very good determinant for composite volume values. This may imply that determination of plant area cover measurements is dependant on the very low water flow velocities within macrophyte patches and their interaction with the water flow velocities outside and around the macrophyte patches (Fortner and White, 1988; Green, 2005b; Marshall and Westlake, 1990; Wharton *et al*., 2006).

On the Bere Stream total fine sediment volume within *Ranunculus* patches had the most significant linear relationship with corresponding values of total composite plant volume, which was followed by the total plant area. The null hypothesis is thus rejected on the Bere Stream, because seasonal fine sediment deposition and storage within *Ranunculus* patches appears to be dependent on corresponding changes of patch cover and volume.

However this was not the case at Frome Vauchurch, where total fine sediment volume within patches was not so well associated with total areal cover or composite volume. Therefore the first null hypothesis is accepted, as this result implies that the retained fine sediment within plant patches on the River Frome was not linked to the physical attributes of the plant, and possibly more dependant on the position of the plant in the stream channel. This may also suggest that the retention of fine sediment within *Ranunculus* patches at Frome Vauchurch was subject to a threshold level of retention. A previous study on CPOM retention within vegetated lowland streams in the USA also acknowledged the possible presence of a threshold level of retention, and when this level is reached the hydrodynamic drag returns matter to transport (Koetsier and McArthur, 2000).

It was apparent that the seasonal variability of the total area cover of *Ranunculus* plants on the Bere Stream was associated with the quantity of fine sediment retained within each patch. It was most likely that the accumulation of fine sediment was the result of decreasing flow velocities within patches, which subsequently decreased the impact of boundary shear stress leading to decreased particle entrainment (Sand-Jensen, 1998; Sand-Jensen and Mebus, 1996). Ultimately, it is more likely that the combination of fine sediment supply and patch growth, combined with the interactions of turbulent and laminar flow that are created in part by the plant itself, determine the patterns of sediment retention (Sand-Jensen, 1998).

The distribution of fine sediment within each *Ranunculus* patch appeared to be unique. Fine sediment was found to extend downstream of the rooted area between January 2009 and July 2009 at both field sites. This finding concurs with observations made by Cotton *et al*. (2006) within their study patches on the River Frome and Sand-Jensen (1998) on his patch studies in Danish sand-bed streams.

This study did not include detailed measurements of water flow velocities within patches because previous studies have reported how spatial patterns in flow velocities within and around macrophyte patches can determine changes in fine sediment (Cotton *et al*., 2006; Marshall and Westlake, 1990; Nepf *et al*., 2007; Nepf, 1999; Sand-Jensen, 1998; Sand-Jensen, 2003; Sand-Jensen and Mebus, 1996; Sand-Jensen and Pedersen, 1999; Wharton *et al*., 2006) and associated feedback relationships that develop between macrophyte patches and flow velocities (Corenblit *et al*., 2007; Luhar *et al*., 2008). The expansion of fine sediment from the rooted area of plants within the Bere Stream began as the total area cover and rooted area increased. A possible suggestion could be that the rooted area became less dense from January 2009 through to July 2009 with fewer rhizomes and stems per unit area. This coupled with the reconfiguration of the patch may have created conditions where higher water flow velocities were able to penetrate further into the stand due to decreased drag (Nepf *et al*., 2007). This may have resulted in increased transport of fine sediment further into the middle of the *Ranunculus* patches. No observations made at either field site where fine sediment was totally absent from the rooted area of each *Ranunculus* patch, suggesting that the most upstream tip or head of the patch is a highly retentive area for fine sediment. The results also suggested that the accumulation of fine sediment within *Ranunculus* patches may be a collection of smaller sediment patches that have varying connectivity within each plant throughout an annual cycle of growth.

6.2.2 Variability in fine sediment characteristics between *Ranunculus* patches from July 2008 to July 2009

Most fine sediment characteristics were not significantly different between the three *Ranunculus* plants at both sites, with the exception of effective D_{50} values at both sites and values of particle sorting S_0. On this basis the null hypothesis can be accepted at both sites with the exception of values for effective particle size D_{50} and particle sorting S_0.

6.2.2.1 Variability of mean particle D_{50} values between plants

Ranges of mean particle D_{50} values were generally restricted between the fine and medium sand within both effective and absolute sediment samples on the Bere Stream and at Frome Vauchurch. The trapping of majority sand-sized particles (63 - 1000 μm) within plant stands concurs with other studies on lowland streams, especially those in UK chalk streams (Cotton *et al*., 2006; Heppell *et al*., 2009; Wharton *et al*., 2006). Work by Sand-Jensen (1998) in a Danish sand-bed stream demonstrated that macrophyte patches retained particles that were between the very fine and fine sand (230 to 448 μm). Similarly, a study by Wharton *et al*. (2009) on Bere Stream at Snatford Bridge found that a large proportion of the effective sediment sampled from a *Ranunculus* stand were between the very fine and medium sand. Additionally, work by (Cotton *et al*., 2006) revealed that absolute sediment samples taken from *Ranunculus* stands on the River Frome were dominated by fine to medium sand.

The dominance of sand-sized particles within effective and absolute sediment samples in this study suggests that the majority of underlying sediment is derived from sediment moving in saltation (Cotton *et al*., 2006; Phillips and Walling, 1999) or as other forms of bedload material (Wharton *et al*., 2006). It is clear that *Ranunculus* and other similar aquatic macrophytes act as a non-selective physical barrier which removes sediment particles from transport (Wharton *et al*., 2006).

On the Bere Stream at Snatford Bridge differences in particle D_{50} were found between the three plants in the January 2009 and March 2009 sample months for both effective and absolute sediment. Additionally, the significant differences between the three plants were the same for the effective and absolute sediments in both months. This implies that there were consistent differences in the temporal retention and storage of effective and absolute fine sediment fractions between the plants at this time. This suggests that there was no difference in the supply or interception of organic and inorganic fine particles between the three plants.

On the River Frome there were no significant differences in the absolute particle D_{50} values between the three plants. This suggests that all three plants retained absolute sediment particles of similar size throughout the one year period. However, there were differences found between the three plants within the effective sediment, suggesting that effective sediment particles were retained differently between the three plants in

November 2008, March 2009 and May 2009. This may be the result of differences in the supply of effective particles to the plants, rather than differences in the physical morphology of plants. The supply of deposited effective sediment particles may have been from a mixture of autogenic and allogenic sources. The autogenic sources may have been introduced in the form of faecal pellets from deposit-feeding and suspension-feeding invertebrates like Simuliidae larvae (Wharton *et al*., 2006). Differences in invertebrate population densities could have great impacts on the interception and processing of particles in the form of spiralling (Wotton *et al*., 1998). It has previously been suggested that faecal pellets can make up the bulk of fine sediment in running waters (Ladle, 1990), and that these can form a large proportion of the deposited fine sediment (Ladle and Griffiths, 1980). Allogenic sources of organic particles are those transported from upstream with mineral particles, but this source is often an unpredictable and dynamic within most rivers (Newbold *et al*., 1981; Vannote *et al*., 1980).

On the Bere Stream few significant differences were found between sample months for values of particle D_{50}. The major similarity between effective and absolute samples was that July 2008 appeared to be significantly different to the other sample months. In general it implies that there were few differences in the values of particle D_{50} within both the effective and absolute sediment samples between sample months. The three plants were generally intercepting and retaining fine sediment with similar particle size characteristics throughout the one year period.

On the River Frome at Frome Vauchurch there were many significant differences found between the sample months for values of particle D_{50} within both effective and absolute sediment samples. It suggests the three plants were intercepting and retaining fine sediment particles of different sizes throughout the one year sampling period.

6.2.2.2 Variability in the volume of silt and clay sized particles between plants

There were no apparent seasonal patterns in the absolute or effective mean % volume of silt and clay sized particles (%SC, <63 μm) within plants on the Bere Stream or at Frome Vauchurch. There were few significant differences found between sample months for values of %SC within both the effective and absolute sediment from either site. The few significant differences suggest that the three plants located at both sites were intercepting and retaining similar volumes of silt and clay sized particles throughout the one year sampling period. This may also indicate that the supply of silt and clay sized particles within both fractions tended to fluctuate very little throughout the sample period.

Within the Bere Stream, values of mean %SC were greater within the absolute sediment in comparison with the effective fraction with values exceeding 10 %. In the majority of the sample months, all three plants were determined not to be significantly different for values of % SC within the effective and absolute sediment. The largest differences were within the January 2009 survey month for both effective and absolute sediments. The differences between plants may have been brought about by the onset of increased winter channel discharge.

On the River Frome at Frome Vauchurch the mean %SC values of the three plants appeared to be different to one another. But the statistical analyses between plants for values of %SC suggested that generally there were no significant differences between the three plants, with the only difference found in May 2009.

The majority of silt and clay sized particles are transported in suspension (Gordon *et al*., 2004; Wharton *et al*., 2006). Additionally, it has been determined in previous studies that the majority of suspended loads within chalk streams comprise of particles that are less than sand (<63 μm) (Acornley and Sear, 1999; Walling and Amos, 1999). Therefore it can be assumed that the three plants on either site were able to intercept silt and clay sized particles from suspension to a more or less similar capacity throughout the year. Additionally, it may have been possible that faecal pellet aggregates had accumulated and contributed to the <63 μm fraction within the plants from filter feeding invertebrates, such as simuliid larvae living on the plant fronds (Wharton *et al*., 2006; Wotton *et al*., 1998). Faecal particles are highly organic (Wotton and Malmqvist, 2001), and it is possible that this is one of the main sources of organic particles found within fine sediment from *Ranunculus* patches (Ladle and Griffiths, 1980).

There are few previous studies that have measured silt and clay sized particles from sediment samples taken from individual aquatic macrophytes. The study by Cotton *et al*. (2006) measured the % volume of absolute sediment particles from two individual *Ranunculus* plants on the River Frome. Their work found that the % volume of silt and clay sized particles (<63 μm) within the absolute sediment from both plants was generally less than 10 % in all of their samples. This is comparable with the results of this current study.

In comparison, the work by Wharton *et al*. (2006) analysed monthly effective sediment samples from a *Ranunculus* stand on the Bere Stream. They found that there were very high volumes of silt and clay sized particles within their samples, with the majority of months possessing between 10 and 20 %. But within a number of sample months they also found considerably higher volumes of silt and clay sized particles within their sediment samples, with the highest estimate value as 48 %. The values for % volume of silt and clay sized particles presented by Wharton *et al*. (2006) were generally much greater in comparison with those from this current study. This perhaps highlights the ephemeral, dynamic nature of fine particulate transport within all streams and rivers (Newbold *et al*., 1981).

6.2.2.3 Variability in the sorting of sediment particles between plants

There were considerable significant differences found between the sample months for values of S_0 in the effective sediment in comparison with the absolute sediment on the Bere Stream. This suggests that the effective sediment possessed considerably variable particle sorting between sample months, in comparison with corresponding values from the absolute sediment fraction for the same sample months. On the River Frome there were no significant differences between sample months for values of S_0 within the absolute sediment fraction. In comparison, there were a number of significant differences found in the values of S_0 within the effective sediment fraction between sample months. This suggests that the addition of the organic particles to fine sediment created the differences in the sorting of effective sediment particles between sample months. This may be because the effective sediment is a combination of organic and mineral particles that are commonly aggregated (Wharton *et al*., 2006).

On the Bere Stream a significant difference was found between the three plants for S_0 values within the effective sediment in January 2009. In general, there was very little difference between the three plants on the Bere Stream regarding values of S_0 within both sediment fractions. Particle sorting values were found to be similar between effective and absolute sediment fractions with the majority of mean S_0 values ranging between 0.50 and 0.69.

In comparison, there were many significant differences found between the three plants for values of S_0 on the River Frome. The results determined that the three plants were significantly different to one another regarding values of S_0 between the November 2008 and May 2009 sampling months in both the effective and absolute sediment fractions. This suggests that the degree of particle sorting between the three plants within both the effective and absolute sediment fractions was completely different during those times of the year. Not many significant differences were found in the values of particle D_{50} and %SC between the three plants from the November 2008 to May 2009 sample month. It is possible that the degree of particle sorting within each of the three plants was dependant on the interactions between the morphology of each plant and the local flow conditions around each plant. Also there it is a possibility that there was another unmeasured parameter that had an impact.

The plants from Frome Vauchurch possessed a greater range of mean particle sorting values within both the effective and absolute sediment fractions in comparison with the three plants on the Bere Stream. There are no previous studies that have analysed the sorting of sediment particles within aquatic macrophyte patches to compare with the data from this current study.

6.2.2.4 Variability in the % organic matter content between plants

There were no clear seasonal patterns in the mean % organic matter content (%OM) within the three plants at either study site.

Within the Bere Stream, the only significant difference found between the three plants was in September 2008. This indicates that the amount of organic matter within the three plants on the Bere Stream was generally similar throughout the whole sample year with the exception of the September 2008 sample month where organic matter was much greater than the other sample months. At Frome Vauchurch the November 2008 and May 2009 sample months were the only months in which %OM values between the three plants were very different. Within these two months it was only one plant that possessed significantly different values of %OM. In general all three plants appeared to posses similar amounts of organic matter within their patches throughout the sampled year. Additionally, the absence of significant differences between sample months for values of %OM at Frome Vauchurch suggested overall there were no differences between sample months for the % organic matter within the fine sediment.

A similar study by Sand-Jensen (1998) found that there were differences in the contents of organic matter between plant patches. He concluded that variations in organic matter content were the result of differences in morphology and the extent of the rooted sections within plant patches, near bed flow velocities, as well as the sediment supply and deposition characteristics of the site. This also corresponded with the findings from Cotton *et al*. (2006) who determined that organic matter content of sediment from morphologically comparable *Ranunculus* patches on the River Frome related to the supply of sediment and trapping efficiency of the plant patches.

The plants at the Bere Stream possessed greater values of %OM within their stored sediment, in comparison with the three plants at Frome Vauchurch. Mean %OM ranged between 1.4 to 9.7 % on the Bere Stream, with the majority of mean %OM values below 5 %. In contrast the mean %OM values on the River Frome ranged between 1.4 and 6.0 %, with the majority of mean %OM values being <3 %. These results concur with the findings of Heppell *et al*. (2009) who investigated the % organic matter within mid-channel vegetation dominated by *Ranunculus* on the River Frome at Maiden Newton and the Bere Stream at Snatford Bridge between March 2003 and November 2004. The values of % organic matter within their study were approximately 2 to 32 % on the Bere Stream at Snatford Bridge and 2 to 7 % on the River Frome at Maiden Newton. These values of % organic matter generally correspond with the findings in this current study. Although the uppermost values of % organic matter from *Ranunculus* on the Bere Stream within their study were conspicuously greater than those within this current study.

6.2.3 Fine sediment characteristics in different zones of *Ranunculus* patches from July 2008 to July 2009

The findings in this study suggest that in general there were no seasonal patterns in mean particle D_{50} values, mean volumes of silt and clay sized particles or mean particle sorting values within the effective or absolute fine sediments in any of the five zones within *Ranunculus* on the Bere Stream or Frome Vauchurch. Additionally, there was no seasonal variability in mean % organic matter values between the five zones within

Ranunculus patches at either site. Therefore, the null hypothesis that particle characteristics do not vary in between different zones within *Ranunculus* patches can be accepted at both sites.

Values from the July 2008 sample month were conspicuous within both absolute and effective sediment fractions on both sites. There appeared to be a greater variation between zones within *Ranunculus* patches at both sites in July 2008 for mean D_{50}, volumes of silt and clay sized particles as well as particle sorting. Mean D_{50} values of effective and absolute fractions at both sites were within the fine to coarse sand grade. July 2008 had the greatest range of mean D_{50} particle sizes between zones within the plants, from the medium to coarse sand in the Bere Stream and fine to coarse sand in the River Frome. The variability between zones at both sites was subsequently reduced in the following sample months. The majority of effective and absolute mean and median particle sizes in all zones were within the medium sand at the Bere Stream and River Frome between September 2008 and July 2009.

It may be suggested that the sampling in July 2008 had disrupted patterns of long term fine particle retention and storage within plants. But, it is more plausible that the differences reflect similar temporal variations in the supply of fine sediment within both rivers that are driven by other hydro-geomorphological factors.

In this study it was observed that the head zone of *Ranunculus* on the Bere Stream possessed much smaller mean D_{50} values within the absolute fraction within the majority of sample months. In addition, the head zone within *Ranunculus* on the Bere Stream possessed the greatest values of silt and clay volumes in both fractions, with the single exception being the effective fraction in March 2009. This corresponds with observations on the River Frome where the head zone and tail zone had consistently smaller and larger mean particle D_{50} values correspondingly, throughout the sampling period. It was also observed that the tail zone also had notably smaller volumes of effective and absolute silt and clay particles. This indicates that fine sediment particles with smaller diameters were present within the head zone of patches in comparison with other zones of the plants. Fine sediment samples from the head zone of patches were always taken within the rooted area in the most upstream section of the plant. The rhizomes and roots within this part of the plant may have increased the retention and storage of finer sediment particles through greater reductions in flow velocities and modifying the shear boundary layer (Sand-Jensen, 1998).

The larger mean D_{50} particle sizes and lower volumes of silt and clay particles in the tail zones of patches in the River Frome suggest that the retention capacity for finer particles in the tail zone is much less than that of the head zone. A similar pattern was also found in *Ranunculus peltatus* (Shrank) within sand bed streams in Denmark (Sand-Jensen, 1998), where greater D_{50} particle sizes were present within the trailing downstream end of the patches examined. This may have been due to the greater levels of entrainment and erosion by swaying the trailing tail sections of patches caused by turbulent flow (Sand-Jensen, 1998), coupled with eddies created by the monami effect of the plant (Ackerman, 1998; Nepf and Ghisalberti, 2008; Nepf and Vivoni, 2000; Okamoto and Nezu, 2009).

The results from this study suggested that there were no seasonal variations in fine sediment characteristics between zones within *Ranunculus* patches. It has been demonstrated that the most upstream and downstream zones within *Ranunculus* patches have distinct differences in mean median particle size and volumes of silt and clay in comparison to other zones within the patches. This study was not able to demonstrate that consistent spatial patterns of fine sediment characteristics exist within the middle and lateral parts of *Ranunculus* patches.

Findings from this current study imply that the spatial distribution of fine sediment characteristics within *Ranunculus* patches are predominantly controlled by the combination of fine sediment supply to the plants and local hydro-geomorphological conditions within the channel. It was also demonstrated that *Ranunculus* patches have an influence in the longitudinal arrangement of fine sediment characteristics, akin to the findings of Sand-Jensen (1998) in *R. peltatus* on sand bed streams in Denmark.

The comparison of *Ranunculus* patches between the two sites within this study demonstrates that interpretation of results is largely site-specific, with perhaps little scope for comparing *Ranunculus* patches between rivers, unless the hydro-geomorphological characteristics prevalent within the study channels are highly comparable. It should be acknowledged that it is often difficult to find analogous macrophyte patches with similar morphological characteristics growing in equivalent geomorphological and hydrological conditions, even at the same site. This is a reflection of the general challenge in obtaining reliable and consistent results from field-based observations involving biological specimens.

Furthermore, the results of this study suggest that more information on the spatial patterns of fine sediment characteristics could be determined using arbitrary dissection of *Ranunculus* patches if sample sizes are greater. It was originally assumed that the sample sizes of this study were sufficient to observe interactions within patches. In hindsight, it was acknowledged that increasing sample sizes may have greatly increased the representation of the findings, and led to the inclusion of statistical tests to further interpret the results.

CHAPTER 7

Conclusions and Implications for Future Research

7.0 Introduction

Section 7.1 of this chapter summarises the key findings in relation to the main research aims presented in the previous three chapters and discusses their implications and wider relevance. Section 7.2 specifically considers the implications of the research findings from this study, including some methodological considerations, for future research on fine sediment dynamics within lowland rivers.

7.1 Key findings and the wider implications

7.1.1 The influence of seasonally-changing macrophyte cover on fine sediment storage and deposition at the reach scale

The first aim of this study was to investigate how seasonally-changing in-channel vegetation controlled fine sediment deposition and storage at the reach scale within two lowland streams.

The outcome of this study suggested that macrophyte patches and the vegetated margins have a considerably higher capacity for fine sediment deposition and storage in comparison with unvegetated parts of the channel. This agrees with the findings of other previous studies within vegetated streams and rivers (*c.f.* Asaeda *et al*., 2009; Corenblit *et al*., 2009; Gurnell *et al*., 2006 and Heppell *et al*., 2009) and is due to their influence on flow velocities and increasing roughness within the channel (Bal *et al*., 2011; Biggs, 1996; Dawson and Robinson, 1984; Gregg and Rose, 1982; Kleeberg *et al*., 2010; Sand-Jensen and Mebus, 1996; Sand-Jensen and Pedersen, 1999).

Fine sediment was restricted to discrete macrophyte patches and marginal vegetation at both sites. The vegetated within-channel margins on the Bere Stream appeared to be significant as stores for fine sediment, especially where *Apium* and *Nasturtium* were seasonally dominant. On the Bere Stream *Nasturtium* patches possessed significantly deeper deposits of fine sediment in comparison with *Ranunculus* patches, with the exception of summer months where sediment depths were not significantly different between *Ranunculus* and *Nasturtium*. Additionally, fine sediment deposits were substantial within the in-channel marginal areas on the River Frome in particular where the margins were dominated by dense terrestrial shrub species such as bramble (*Rubus fructosis*).

Emergent *Ranunculus* patches on the Bere Stream possessed significantly greater depths of fine sediment in comparison with submergent patches. The opposite relationship was observed on the River Frome, where fine sediment depth was greater within submergent *Ranunculus* patches in comparison with emergent patches. This is in agreement with the observations by Asaeda *et al*. (2009) who found that differing morphologies of *Sparganium erectum* interacted with surrounding flow velocities which in turn influenced fine sediment deposition within patches. This could reflect the supply of fine sediment particles from upstream, with greater concentrations of fine sediment present in suspension on the Bere Stream, in comparison with that of the River Frome at Frome Vauchurch. However, this is unlikely as the suspended sediment samples taken in this study between January 2009 and July 2010 indicate that the River Frome possessed greater concentrations of suspended sediment during the study period. A further possibility is that the difference in water depths between the Bere Stream and River Frome may have had some influence on near-bed flow velocities, which in turn may impact the deposition of fine sediment within *Ranunculus* patches. Similar observations were made within macrophyte patches on Danish sand-bed streams in the study by Sand-Jensen (1998).

Submerged aquatic macrophytes and encroaching vegetation growing from the banks can be beneficial and detrimental for lowland streams and rivers. The benefits of in-channel macrophyte and bank vegetation growth include the provision of niches for invertebrates as well as terrestrial and aquatic vertebrates (Moss, 2010). Marginal vegetation has been determined as beneficial for fish species for foraging and as nurseries for juvenile fish (Pedersen and Friberg, 2009; Pretty *et al*., 2003). Certain aquatic invertebrates rely on in-channel and riparian vegetation for food resources (Pedersen and Friberg, 2009) and fulfilling parts of their lifecycles such as ovo-depositing and metamorphoses (Garner *et al*., 1996; Kaenel *et al*., 1998; Moss, 2010; Thorup *et al*., 1987). Streamlined in-channel macrophytes like *Ranunculus* found within UK chalk streams are beneficial as a refuge from higher flow velocities and as an attachment for invertebrates (Bal *et al*., 2011; Iversen *et al*., 1985; O'Hare *et al*., 2007b; Roussel *et al*., 1998; Wright *et al*., 2002). Additionally, riparian and marginal vegetation protects the banks from being degraded and eroded by increases in channel flow and wave action (Dosskey *et al*., 2010; Hubble *et al*., 2010), which subsequently prevents further decreases in water quality due to increased sediment loss and transport.

It should also be noted that the seasonal growth and recession of in-channel macrophytes are imperative in regulating channel hydrology. It has observed that the growth of in-channel aquatic macrophytes can artificially increase the water stage of lowland streams in the summer (De Doncker *et al*., 2009; Kaenel *et al*., 1998) including southern English chalk streams (Hearne and Armitage, 1993). This can help prevent severe low flows and the 'drying-out' of lowland streams in the summer months due to anthropogenic impacts such as excessive water abstraction (Acreman *et al*., 2008; Hearne and Armitage, 1993; Wood and Petts, 1999). Low flows can have negative impacts on the ecology of streams and rivers, as well as increasing localised fine sediment deposition (Dunbar *et al*., 2010; Humphries and Baldwin, 2003).

In-channel aquatic macrophytes within lowland gravel-bed streams can act as temporary stores for fine sediment in the summer whilst the associated higher flows around patches remove fine sediment deposits from the coarse gravel strips in between plant patches (Asaeda *et al*., 2009; Kleeberg *et al*., 2010; Wharton *et al*., 2006). This is beneficial as they facilitate the removal of fine sediment from gravel in addition to promoting localised seasonal 'locking-up' of fine particulate sediment within discrete patches (Cotton *et al*., 2006; Sand-Jensen, 1998; Wharton *et al*., 2006). Traditionally, these patches of fine sediment are entrained after physical removal of the associated plant by increased winter channel discharge (Butcher, 1933; Kleeberg *et al*., 2010).

The growth of aquatic macrophytes may become problematic when dominant seasonal macrophytes such as *Ranunculus* persist over winter, as observed on the River Frome in this study. In these cases it is possible that significant accumulations of fine particulate sediment are stored over prolonged periods within vegetated reaches, with potential sediment-associated contaminants being retained as well (Armitage *et al*., 2008; Droppo and Stone, 1994; Fleeger *et al*., 2003). The prolonged storage of fine sediments may lead to high localised levels of colmation within vegetated sections of the gravels.

Additional disadvantages related to the growth of aquatic macrophytes and dense riparian vegetation is the physical blockage of channel flow which has been associated with considerable fine sediment retention within streams in previous studies (Wood and Armitage, 1997; Wood and Petts, 1999). Furthermore, it has been recommended that vegetation and weed within channels should be continually managed to increase potential conveyance of channel flow and allow adequate water drainage from terrestrial sources in EU and UK Government-headed advisory documents such as the Pitt Review (Pitt, 2007).

A persisting problem is one where a 'one-approach fits all' solution is developed for in-channel macrophytes and marginal vegetation at the scale of a catchment or river. It has been demonstrated in previous studies that although the overall symptoms relating to increased sediment deposition are similar within different gravel-bed streams and rivers, the causes and impacts are often localised with dense aquatic macrophyte growth implicated as an associated problem (Armitage *et al*., 2008; Environment Agency, 2001; Environment Agency, 2004). The impact of aquatic macrophytes and riparian marginal vegetation on flow hydraulics and associated fine sediment deposition is generally site or reach specific. This can be the result of river and catchment wide fine sediment problems (Corenblit *et al*., 2009; Corenblit *et al*., 2007).

Therefore, it could be suggested that management should initially tackle fine sediment problems by attempting to identify the provenance of fine sediment using the fingerprinting technique *c.f.* (Carter *et al*., 2003; Collins *et al*., 1997; Walling and Amos, 1999) which remains the only effective and reliable method of determination to date (Walling and Collins, 2005). In using this technique it is possible to attempt to trace the point where fine sediment particles enter watercourses within a catchment. Once these points are identified further management practices can be employed to prevent localised sediment erosion and loss, with a view to commencing management in the upstream of the catchment and working in the direction of down stream.

Fine sediment sampled within *Ranunculus* patches at both sites in this study was dominated by seasonally variable sand-sized particles in both effective and absolute samples throughout the two year investigation with smaller volumes of silt and clay sized particles. Significant differences were found between sample months for values of particle D_{50} and the % silt and clay-sized particles within both effective and absolute sediment fractions and bulk density at each site. Additionally, the highly significant differences found between the effective and absolute fractions for particle D_{50} values and % silt and clay sized particles suggest that there are differences between the two fractions within *Ranunculus* patches on the Bere Stream.

The provenance of fine sediment particles (<2000 μm) has been analysed on the River Piddle (Walling and Amos, 1999), with the origin of silt and clays (<63 μm) analysed for both the River Frome and River Piddle (Collins and Walling, 2007b). The sand-sized sediment fraction (63-2000 μm) was found to be the greatest component of deposited fine sediment within *Ranunculus* patches on the Bere Stream and the River Frome in this study and in previous studies (Cotton *et al*., 2006; Heppell *et al*., 2009; Wharton *et al*., 2006) but the provenance of sand-sized particles within the Frome-Piddle catchments has yet to be analysed (Heppell *et al*., 2009).

The organic matter content of fine sediment was highly variable within *Ranunculus* patches between sample months during the two year study on the Bere Stream at Snatford Bridge. While there was also a highly significant difference between sample months for % organic matter content on the River Frome at Frome Vauchurch, the majority of the difference lay between sediment samples taken in July 2010 and those sampled within previous months. Previous studies involving nutrients associated with fine sediment have observed peak concentrations of nutrients during the summer months within deposited fine sediment in macrophyte patches (Schneider and Melzer, 2004; Wigand *et al*., 2001) and in the suspended fine sediment within British rivers (Walling *et al*., 2001). Additionally, it has been suggested that the increased trapping of fine particulate sediment by aquatic macrophytes at peak growth in the summer resulted in higher concentrations of nutrients (Schneider and Melzer, 2004; Wigand *et al*., 2001).

7.1.2 The impact of seasonally-changing macrophyte cover on fine sediment transport at the reach scale

The second goal of the investigation was to observe how seasonally-changing macrophyte cover and composition influence fine sediment transport. Decreases in the values of F_X and increases in values of K_P for corn pollen were not significantly correlated with increases in total macrophyte cover or *Ranunculus* cover on the Bere Stream or River Frome.

This suggests that increases or decreases in fine sediment transport at both sites do not vary correspondingly with values of macrophyte cover. Therefore, it is not possible to estimate the transport of fine sediment through a vegetated reach based on values of macrophyte cover. However, values of F_X were found to be considerably decreased at both sites when the cover of macrophytes was highest and discharge values were lowest in May and July 2009. Patches of in-channel macrophytes at both sites were most likely acting as a semi-permeable barrier or sieve for the fine particulate matter being transported into the reach (Champion and Tanner, 2000; Watson, 2007). It is possible that the physical presence of macrophyte patches has a greater influence on fine sediment particle transport than conveyance of water within the channel (Bal *et al*., 2011; Kleeberg *et al*., 2010). This effect on sediment transport was possibly enhanced by plant reconfiguration into wider patches due to the seasonally lower flow velocities associated with decreased channel discharge (Green, 2005a; O'Hare *et al*., 2007a; Sand-Jensen, 2003; Statzner *et al*., 2006).

The values of F_X, S_P and K_P for corn pollen particles did not correlate with corresponding values of channel porosity within the two lowland streams. This suggests that the transport of corn pollen particles through both streams was not dependant on the quantity of unvegetated, higher velocity water within the reaches. In addition, values of V_{dep} were not correlated with changes in total macrophyte area cover, the area cover of dominant macrophyte species, or values of channel porosity within either reach. Changes in V_{dep} values within vegetated lowland streams may be influenced by a hydrological or geomorphological factor that is dependant or independent of seasonal aquatic macrophyte growth. It was not possible to identify what the underlying factor may be from the results of this study. Warren *et al*. (2009) found that both K_P and V_{dep} values varied greatly in flume experiments between releases of corn pollen in a normal gravel bed and one that had been infilled with fine sand. Within their first flume release in June 2004 Warren *et al*. (2009) found that values of V_{dep} were 20 times greater in a flume where the gravel was artificially infilled with sand (9.34 mm s^{-1}) in comparison with the gravel prior to colmation (0.46 mm s^{-1}). Colmation could be the additional factor that has a considerable influence on fine sediment transport within seasonally vegetated streams, and further research is required.

Previous studies have acknowledged that increased seasonal growth of macrophyte patches within lowland rivers and streams can impact water conveyance within those channels, leading to increased water stage and occasional flooding of the riparian fringe (Hearne and Armitage, 1993; Holmes, 1999). It has previously been assumed that increased macrophyte and vegetation growth in channels would decrease sediment transport (Iversen *et al*., 1993). The results of this study suggest that this assumption is plausible within the lowland streams studied, especially in the summer months when growth and cover is at its peak and channel discharge is at its lowest.

Therefore, seasonal management of aquatic macrophyte growth may be necessary to improve fine sediment transport within vegetated stream channels.

Lowland streams like the UK chalk streams which possess seasonally high macrophyte growth have traditionally been managed using rudimentary, laborious and often costly weed-cuts (Moss, 2010). A further technique using a 'half-shade' approach to limit the amount of light penetration to the water's surface by planting trees on the north facing bank has also been previously proposed (Dawson and Kernhansen, 1979; Moss, 2010).

The traditional approach to weed-cutting in vegetated UK lowland streams has been the removal of all macrophytes in the centre of the channel leaving alternating marginal fringes of up to 20 m in length (Environment Agency, 2009; Garner *et al*., 1996; National Rivers Authority - Anglican Region, 1994). However, it has been observed that weed-cutting can lead to a loss of biodiversity, with Pedersen and Friberg (2009) describing it as 'detrimental' and to be avoided unless absolutely necessary. Additionally, weed-cutting can be expensive due to its manual nature, with the Environment Agency in the UK currently spending £8 million annually on weed-cutting and weed-removal from rivers and streams in England and Wales (Environment Agency, 2011b). It is now clear from the findings of this current study that the decision of how and what to cut within any channel has to be increasingly holistic by considering all of the features present at a site including the geomorphology, ecology and hydrology. This is especially true in English chalk stream habitats where *Ranunculus* beds and associated fauna are of high nature conservation importance, and have been designated a priority habitat under the EC Habitats Directive (92/43/EEC) (Wright *et al*., 2002).

This study suggests that surgical localised seasonal weed-cutting is the best option of management for vegetated lowland reaches, which agrees with the findings of previous studies (Garner *et al*., 1996). The management requirements for both reaches used in this study would have to be approached in separate ways due to the differences in the ecological, hydrological and geomorphological characteristics at both sites. However, it can be suggested that careful cutting of longitudinal strips through the dense *Ranunculus* growth at its peak in summer to reduce cover to ~50 % is perhaps the best management option for both study sites during the summer. Although the exact amount of vegetation to remove would depend on the extent and distribution of macrophyte growth, as well as other factors such as channel discharge. This would mitigate flooding during summer and autumn spates in addition to increasing the capacity of fine sediment transport through the reach. Additional removal of marginal macrophyte species such as *Apium* and *Nasturtium* on the Bere Stream may also increase fine sediment transport through the reach by preventing considerable sediment deposition and storage within the marginal areas.

There is a current knowledge gap in determining whether active management can achieve a balance between fine sediment transport and water conveyance through reaches whilst mainting the river's ecological. Further experimental work is required to investigate how weed-cutting and other management practices influence flows of water and fine sediment through vegetated reaches with associated monitoring of ecological, hydrological and geomorphological parameters.

7.1.3 The temporal and spatial changes of fine sediment deposition and particle characteristics within *Ranunculus* patches.

The third aim of this thesis was to examine the temporal and spatial changes in fine sediment deposition and particle characteristics within *Ranunculus* patches at the patch scale.

The rooted area of plants was well correlated with the total plant area on the Bere Stream, but this was not the case on the River Frome. There was a less pronounced seasonal growth pattern of aquatic macrophytes on the River Frome in comparison with the Bere Stream. Fine sediment remained within the rooted section of plants at both sites, but was distributed downstream within the tail section as total plant area of *Ranunculus* increased on the Bere Stream. The results of this study suggest that *Ranunculus* patches act like a non-selective barrier or stoss for fine sediment, with the majority of fine sediment stored within the head end of the patch. This was similar to the pattern of sediment deposition described within aquatic macrophyte patches on Danish streams by Sand-Jensen (1998) who observed that fine sediment was distributed within the upstream two thirds of plants and was usually associated with the rooted areas of aquatic macrophyte patches. He suggested this was due to decreasing near-bed velocities within the rooted area, which led to the retention of fine sediment particles varying in size (Sand-Jensen, 1998).

The comparison of *Ranunculus* patches between both sites in this study led to the suggestion that there may be inter-site differences in the growth patterns and morphology of the dominant *Ranunculus* species *R. penicillatus subsp. pseudofluitans*. This has been observed in other species of macrophytes in previous studies, including species of *Ranunculus* such as *R. peltatus* (Garbey *et al*., 2006). The influence of differing seasonal morphologies of *Ranunculus* on fine sediment deposition in this study agrees with the conclusions of a previous study by Asaeda *et al*. (2009) on *Sparganium erectum*. They concluded that the seasonal change in fine sediment deposition within *Sparganium* patches was influenced by changing plant morphology and the interaction with water velocities.

There was little difference between the interception of mineral and organic particles between *Ranunculus* plants at both sites throughout the annual period. There was also a lack of evidence for particle sorting through the different parts of the *Ranunculus* plants. However, the head zone of plants at both sites appeared to possess smaller mean particle D_{50} values in comparison with other zones. Finally, there were no clear patterns of fine sediment distribution (represented as sediment depth) within *Ranunculus* patches at either site, although the low sample size in the study may have contributed to this finding. It was suggested by Sand-Jensen (1998) that the relationships between hydrological functions (water flow velocities and near-bed flow) and sediment parameters are not likely to be accurate for single measurements because of "the influence of multiple probability functions changing over time and space". The work in this thesis supports this view.

7.2 Implications for Future Research

This final section of the thesis highlights areas where further research is necessary to increase understanding how macrophytes may influence sediment transport within lowland streams. Improvements are proposed for enhancing mapping of river macrophytes at the reach scale and employing tracers to investigate reach-scale transport and deposition of fine sediment in vegetated rivers.

7.2.1 Methods of mapping of aquatic vegetation

Within this thesis it was important to obtain a reliable estimate for macrophyte area cover and patch distribution. The method presented within this thesis employed an estimate of cover using data collected from field surveys that were subsequently interpolated within a geospatial computer package. In future, a differential total station could be employed to map the perimeter of macrophyte patches or remote sensing techniques, such as aerial photographs, could be used to derive estimates of macrohyte cover over a wider area.

7.2.2 Reach scale releases and the use of analogue particles

The methodology used for releasing corn pollen in this thesis could be further developed to improve the precision of data acquisition from reach scale releases. Increasing the number of downstream sample points across the river would improve estimates of corn pollen particles in suspension across the cross-section. However, to mimize the impact upon the hydraulic conditions within that part of the channel sampling should ideally be undertaken without having to enter the river.

Replicates of corn pollen releases should also be undertaken to assess thevariability that occurs during a single release experiment using a range of conspicuously labelled or coloured particles that resemble the background particles within the stream to allow differentiation between particles captured from each release.

Further experimental releases could also investigate the use of additional analogue particles to facilitate the development of a range of easily-identifiable analogue particles of varying size and density that could be used to model the transport of both the mineral and organic components of natural river sediments. These could replace the use radio-labelled 'natural' particles were there are concerns about their impact on natural habitats.

7.2.3 Fine sediment transport within vegetated reaches

This study has shown that the effect of seasonal aquatic macrophyte growth on fine sediment transport depends on site-specific interactions between macrophyte patches, channel hydrology and geomorphology. Further long term empirical studies are required to improve our understanding of the relationship between seasonal aquatic macrophyte growth and the fine sediment dynamics.

The experimental approach employed in this study was time and labour intensive both in terms of the field experiments and the laboratory analysis of sediment samples. Continuous measurements of turbidity upstream and downstream of aquatic macrophytes patches within a reach may be a more effective and efficient way of investigating fine sediment transport through vegetated reaches if coupled with estimates of aquatic macrophyte cover as well as regular or continuous measurements, discharge and water flow velocities.

7.2.4 Patch-scale sediment sampling and analyses

This study did not detect the spatial variability of fine sediment particle characteristics within *Ranunculus* patches that was observed by Sand-Jensen (1998). Future research should consider increasing the number of sediment samples taken from different zones within each *Ranunculus* stand, as well as increasing the total number of plant patches within the study. This would ensure that there are enough replicates within the eventual dataset so that statistical analysis could be undertaken.

Additional experiments of sediment trapping and retention within macrophyte patches of different morphologies could be conducted using experimental channels or flumes to control flow and sediment inputs.This would further improve our understanding of how these patches influence localised fine sediment dynamics.

7.2.5 Origins of the sand fraction on the Bere Stream

It is still unknown where sand-sized particles originate from within the Piddle catchment that supplies the Bere Stream. A further investigation could analyse the provenance of sand-sized particles using fingerprinting techniques (Carter *et al*., 2003; Collins and Walling, 2007b; Walling and Amos, 1999; Walling and Collins, 2005). The results of such a study would inform local habitat managers and allow them to improve riparian land practices in order to prevent terrestrial soil loss and reduce its transfer into the river system.

7.2.6 Fine sediment transport and colmation

Additional empirical studies are essential to investigate how colamtion may affect the the transport of fine sediment in lowland gravel-bed streams with seasonal growth of aquatic macrophytes. The flume experiments and the field study presented by Warren *et al*. (2009) indicated that colmation of the gravel bed may decrease transport of fine sediment particles.

Future studies relating to fine sediment transport should seek to measure the extent to which the interstitial space between clasts in bed substratum are colmated or in-filled by fine sediments. Bed samplers can be used to estimate bed storage and the rate of colmation can be measured by determining the mass of fine sediment that accumulates over time within sediment trap boxes that are filled with gravel clasts. Alternatively, a freeze core of a known volume of bed substratum can be taken and its contents analysed to determine the extent to which the gravel in the sample has been in-filled by fine sediment.

Further experimental studies (after Warren *et al*., 2009) could also explore how transport is affected by differing levels of colmation by in-filling the gravel bed with known volumes of fine sediment

7.2.7 Values of V_{dep} within lowland vegetated rivers

This study suggested that the greatest values of V_{dep} at both sites corresponded with high macrophyte cover and low discharge values. However, there was no correlation between values of V_{dep} and macrophyte cover at the two study sites. Further empirical experimental studies performed under controlled conditions within an experimental catchment stream may help to determine which parameters influence values of V_{dep} in vegetated rivers.

7.2.8 Channel porosity values

The calculations of channel porosity used in this study provided estimates of unvegetated flow conveyance or leakiness at both sites. However, there are alternative methodologies and models available that could produce leakiness or water conveyance estimates. The Conveyance Estimating System (Gurnell *et al*., 2010) is a modelling program that allows the user to input hydrological and ecological data values into an idealised channel cross section composed of rectangular cells. By using this approach it is possible to model fine scale conveyance of water through vegetated river and stream channels.

The methods presented in this thesis for estimating absolute and composite plant volumes are one of a number of ways in which the volume of *in-situ* aquatic plant matter can be calculated. Additional existing field and laboratory measurements that quantify plant volume or surface area are required for estimating absolute plant volume within emergent macrophytes species, like those of *Nasturtium* and *Apium*. This would help to increase the accuracy of channel porosity calculations in the future. Further work comparing plant biomass and channel porosity values may be useful for increasing our understanding of how channel porosity relates to variations in seasonal aquatic macrophyte growth.

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APPENDIX

See attached CD for the data analyses and statistical work included with this thesis.