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University of Southampton

Faculty of Environmental and Life Sciences

School of Geography and Environmental Science

The Development of Ecologically Relevant Fine Sediment Targets for Chalk Streams

by

Beth Mondon

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Thesis for the degree of Doctor of Philosophy

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Abstract

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Fine sediment plays an important role in freshwater ecosystems and is critical for their natural functioning, nutrient cycling, and aquatic biota. Chalk streams regularly exhibit substantially higher quantities of accumulated fine sediment in their gravel beds compared with other gravel bed river systems, despite often presenting with lower suspended sediment loads. This is a consequence of their natural hydrological conditions (i.e., low bed mobilising flows) compounded by anthropogenic activities altering channel planforms and increasing fine sediment inputs. This, in combination with their fine sediment-sensitive species, creates a high propensity for long lasting lethal/sub-lethal ecological impacts. Current approaches to defining management targets have failed in chalk streams due to a lack of scientific knowledge underpinning them. Importantly, they have failed to consider individual river system responses to fine sediment and to explicitly link the fine sediment problem with its causation. As a result, there is a need for new and ecological-relevant targets for the dominant process controlling fine sediment accumulation in chalk streams, to prioritise revised management and restoration activities. To identify the key controlling mechanisms in chalk streams, a new conceptual framework was proposed, describing the chalk stream sediment budget. The sediment budget framework incorporated four overarching mechanisms controlling fine sediment accumulation. Stream power (in particular, low bed mobilising flows) was highlighted as the most critical factor, controlling three out of four of these mechanisms. Through construction and analysis of an extensive freeze-core database, the sedimentological characteristics of chalk stream gravel beds were established, as they form a key control on the exfiltration of fine sediment. Analysis highlighted that 89% of chalk stream gravel beds were over-saturated with fine sediment and that 75% had fine sediment quantities exceeding those previously established to cause substantial ecological degradation. Regional variations were attributed to differences in stream power and local sediment sources. It was also determined that current models describing gravel bed-fine sediment interactions were not representative of chalk stream sedimentological characteristics. Through flume experiments, new targets for the flow velocities required to remobilise fine sediment from the ecologically-sensitive surface layer of chalk stream gravel beds were established. The experimental gravel bed and fine sediment grain size distributions were taken from the previously determined chalk stream sedimentological characteristics, to ensure the experimental design better represented naturally occurring conditions. Comparison between the required flow velocities and those currently occurring in chalk streams indicated that, for the most part, chalk streams are not achieving flow velocities required to remobilise fine sediment from the surface layer of their gravel beds. Potential revised instream management and restoration activities to restore the required flow velocities were discussed. The flow velocities provided herein are some of the first scientifically robust targets that can direct revised management and restoration activities, aimed at reducing fine sediment quantities in chalk stream gravel beds. In the absence of targets, the impacts of elevated fine sediment quantities in chalk streams are not being addressed. Until sediment targets are recognised and adapted in policy and process, actions to restore these systems to more favourable conditions cannot be efficiently or effectively implemented or measured.

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Research Thesis: Declaration of Authorship

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I declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

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Definitions and Abbreviations

ADV	Acoustic Doppler Velocimeter
ADVP	Acoustic Doppler Velocimeter Profiler
Av	Avon
Ave	Average
Ba	Babingley
BAP	Biodiversity Action Plan Priority Species
BOD	Biological oxygen demand
$CaCO_3$	Calcium carbonate
CPDG	Cumulative probability distribution of gravels
d	Particle diameter
D_{50}	Median sediment particle
D_g	Geometric mean
D_{gg}	Gravel (framework) geometric mean
D_{sg}	Fine sediment (matrix) geometric mean
DOM	Dissolved organic matter
EPS	Extracellular polymeric substances
EU	European Union
FFD	Freshwater fish directive
FFWS	Fully framework-supported
FMS	Fully matrix-supported
FSF	Fine sediment fraction
Fr	Frome
FWS	Framework-supported
GSD	Grain size distribution
It	Itchen
K	Kurtosis

MS	Matrix-supported
Na	Nadder
NTU	Nephelometric turbidity units
$P_{2.0}$	Proportion of fine sediment <2 mm
P_{62}	Proportion of fine sediment <62 μm
Pi	Piddle
POM	Large particulate organic matter
RCP	Representative Concentration Pathway
RGT	Roughness geometry thickness
S	Skewness
SAC	Special Area of Conservation
SS	Suspended sediment
SSSI	Sites of Special Scientific Interest
St	Stiffkey
T	Transition
Te	Test
TLS	Terrestrial laser scanner
TMDL	Total maximum daily load
UP	Upper Avon
USP	Unimpeded static percolation
σ_g	Geometric standard deviation (sorting coefficient)
σ_{gg}	Gravel geometric standard deviation (framework)
σ_{sg}	Fines geometric standard deviation (infiltrating sediment)
WFD	Water framework directive
Wi	Wissey
Wy	Wylye

Chapter 1 Background and context

This chapter provides the background for the thesis and is divided into seven sections. Initially this chapter gives a definition of fine sediment and a summary of the natural role of fine sediment within river systems, including its sources and transport both within river catchments and channels (Sections 1.1 and 1.2). Section 1.3 describes the long-term increases in suspended sediment yields and fine sediment accumulation within river systems globally and discusses the causes for such changes. The implications of these changes in sediment yields for river systems and the aquatic organisms they support are discussed (Section 1.4). Section 1.5 introduces chalk streams and discusses the fine sediment problem unique to them. Challenges for excessive fine sediment management in river systems in particular chalk streams are discussed in Section 1.6. The concluding Section 1.7 summarises the discussed issues and gaps that need to be addressed.

1.1 What is fine sediment?

Fine sediment in river ecosystems comprises a matrix of inorganic and organic particles, classified as those <2 mm in diameter. Previously the term “fine sediment” was strictly used to describe mineral grains, but improved understanding of river system sedimentology in recent decades has recognised both the organic and flocculated components of fine sediment (e.g., Walling and Woodward, 2000; Droppo, 2001; Woodward and Walling, 2007). The inorganic component of fine sediment consists of mineral particles derived from the chemical and physical weathering of bed rock and includes sand (2 mm – 62 μm), silt (62 – 4 μm) and clay (<4 μm) (Church et al., 1987; Winterwerp and Van Kesteren, 2004), according to the particle size grading proposed by Wentworth (1922). As the particle size decreases, the surface area per unit volume of the particle increases and cohesive (interparticle) forces dominate particle behaviour. Sand-sized particles are mostly comprised of mineral quartz and are non-cohesive. Silt-sized particles are generally considered to be cohesive, dependent on the presence of clay and organic material. Clay-sized particles are cohesive and form the most electro-chemically active fraction of fine sediment (Woodward and Walling, 2007; Kuhnle, 2013).

The organic component of fine sediment consists of a wide range of biogenic compounds and structures. This includes spores, pollen grains, microbes, extracellular polymer substances (EPS), woody debris, invertebrate carcasses, plant fragments and faecal pellets (Wotton et al., 1998; Droppo, 2001; Riis and Sand-Jenson, 2006; Heppell et al., 2009). Organic materials in river systems can range in size from colloidal dissolved organic matter (DOM) to large particulate organic matter (POM) (Winterwerp and Van Kesteren, 2004); the size characteristics of common organic materials (<2 mm), compared with inorganic components are demonstrated in Figure 1.1. Organic material can form a substantial proportion of the fine sediment in river systems; for example, blackfly larvae faecal pellets were demonstrated to account for 40-60% of deposited fine sediment in a chalk stream gravel bed (Wharton et al., 2006). Cohesion and microbial binding (i.e., via the bacterial secretion of EPS) of inorganic and organic particles often causes flocculation and subsequent formation of flocs of individual particles (Droppo, 2001; 2004; Woodward and Walling, 2007; Grabowski et al., 2011). Flocculation of individual particles increases the absolute particle size, changing the effective particle size, density, and porosity and, thus fundamentally alters the hydrodynamic properties of the sediment particle (Droppo, 2001; 2004; Grabowski et al., 2011).

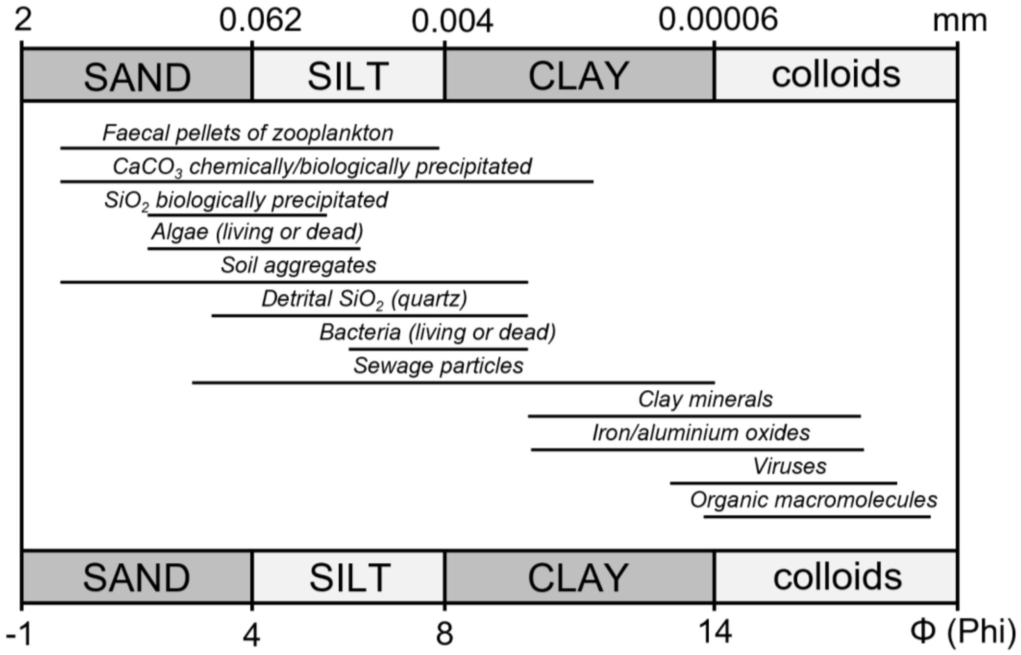


Figure 1.1: Fine sediment (<2 mm) size characteristics, including common organic materials (adapted from Naden, 2011).

1.2 Fine sediment in river systems

The erosion, transport, and deposition of fine sediment by river systems play a critical role in the transport, storage, and recycling of nutrients and contaminants (Clarke and Wharton, 2001; Bowes et al., 2005; Collins et al., 2005; Jarvie et al., 2005). It has been estimated that sediment-associated transport accounts for >90% of the total riverine flux of P, Mn, Ni, Pb, Fe and Al (Martin and Meybeck, 1979). In addition, sediment-associated transport accounts for an estimated 43% of the total organic carbon transfer between land and oceans (Ludwig et al., 1996). Fine sediment is also critical in creating habitat heterogeneity within river systems and plays a fundamental role in numerous critical life-cycle stages of freshwater organisms, including European river lamprey ammocoete (*Lampetra fluviatilis* L.) recruitment (Silva et al., 2015) and burrowing mayflies (*Ephemeroptera*) (Jacobus *et al.,* 2019). Additionally, some aquatic species utilise fine sediment in the construction of refugia; for example, caddisfly (*Trichoptera*) larvae bind fine sediment particles with silk to create mobile cases, fixed retreats, or pupal cases (Okano and Kikuchi, 2012; De Gispert et al., 2018; Mason et al., 2019; 2022). In lowland UK gravel bed rivers, 94% of caddisfly larvae species were identified as utilising fine sediment for case building, using on average 38 g m^{-2} (and up to 139 g m^{-2}) of fine sediment (Mason et al., 2019).

1.2.1 Erosion of fine sediment and delivery to river networks

The source of fine sediment plays a fundamental role in determining sediment physical and chemical properties, including size, composition, and organic content (Walling and Collins, 2005, Walling et al., 2005). Sources of fine sediment in chalk streams include the erosion of soil, anthropogenic activities (e.g., sewage outflows and watercress farming), autochthonous sources (e.g., faecal pellets and plant fragments) and riverbank erosion (Neal et al., 2000; Wharton et al., 2006; Collins and Walling, 2007a; 2007b; Bateman, 2012; Zhang et al., 2017a). One of the primary sources of fine sediment in UK river systems is the erosion of soil, often contributing >70% of accumulated fine sediment in riverbeds (Collins and Walling, 2007a; 2007b; Bateman, 2012). The detachment of individual soil particles and/or water-stable aggregates is determined by a number of processes such as raindrop impact, biological activity, surface runoff, physical weathering, wind, and freeze-thaw cycling (Walworth, 2004; Bracken, 2010; Vercruysse et al., 2017). Substantial soil erosion can also occur due to mass movements such as debris and/or mud flows, soil creeps and rotational slumps (McCool and Williams, 2008; Bracken, 2010).

The erosion of soil is typically caused by raindrop or splash erosion, this occurs when the kinetic energy possessed by the falling raindrop is sufficient to detach soil particles when hitting the soil surface. Raindrops increase the propensity for soil erosion via two processes; topsoil aggregate breakdown and initiation of soil fragment movement (Van Dijk et al., 2002; Legout et al., 2005; Warrington et al., 2009). The detached soil particles can then be entrained by runoff erosion (sheetwash), transporting them away from the point of origin (i.e., source) (Hardy et al., 2017; Pulley and Collins, 2019). Raindrop (splash) and runoff erosion often occur in tandem, as the shear stress of runoff (overland flow) is generally insufficient to initially erode the fine sediment but can transport sediment particles detached due to raindrop (splash) erosion (Singer and Walker, 1983; Guy et al., 1987). The extent of soil erosion is driven mostly by two mechanisms (Figure 1.2) : (1) erosivity, the capacity of the eroding agent (e.g., raindrops or overland flow) to erode the soil, which is influenced by factors including the rainfall drop size and velocity, and; (2) erodibility, the susceptibility of the soil to erode, which is a function of the soil properties such as the surface permeability and soil composition, including physical and chemical properties (Perks et al., 2015; Vercruysse et al., 2017).

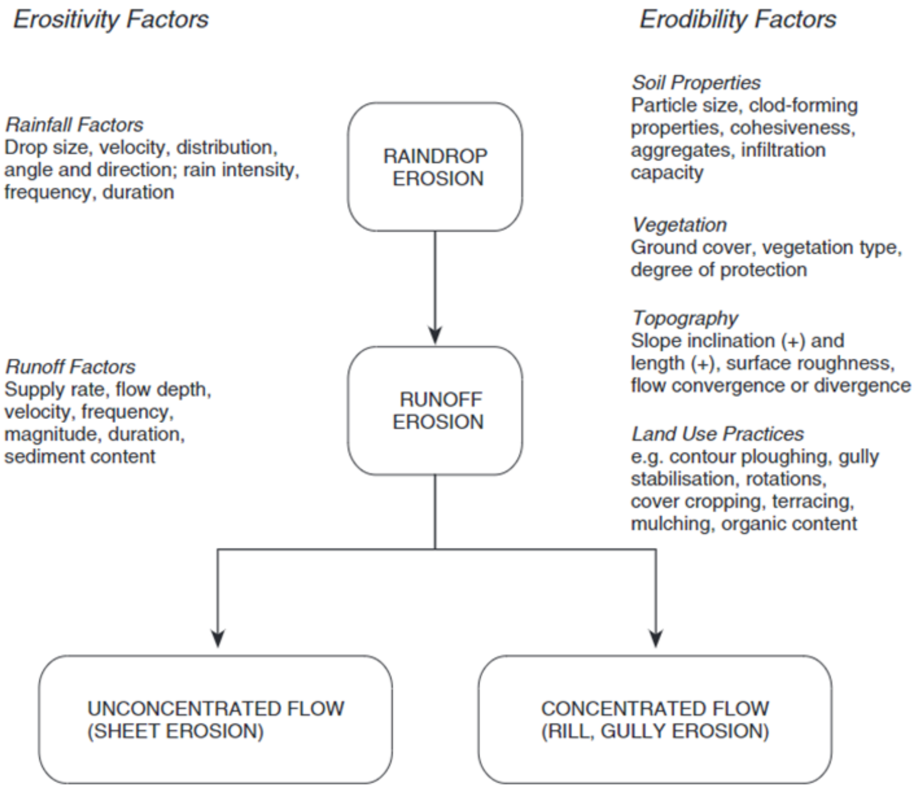


Figure 1.2: Principal factors controlling erosivity and erodibility of fine sediment in river catchments.

There are two processes of overland flow (i.e., surface runoff) generation: (1) infiltration-excess overland flow (Hortonian runoff), which occurs when rainfall rates exceed the infiltration capacity of the soil; and (2) saturation-excess overland flow, which occurs when the soil is already saturated and no further water can infiltrate (Smith and Goodrich, 2006; Bracken, 2010). Saturation-excess overland flow, in combination with raindrop erosion, has been identified as the primary erosion mechanism in lowland grazing fields, in southwest England (Pulley and Collins, 2019). Attributed in part to the semi permeable soils, prone to seasonal waterlogging. Whereas, in fields more prone to crusting due to high silt quantities (>60%) such as in the South Downs (England), the dominant overland flow process can shift from saturation-excess to infiltration-excess during storm events a result of crusting limiting the infiltration rates of the soil (Boardman, 2020). These surface runoffs can either occur as unconcentrated flows (sheetwash erosion) or concentrated flows (i.e., the formation of rills and gullies) (Bracken, 2010; Poesen, 2018). Rills are defined as impermanent channels, characterised by depths <30 cm, with seasonal cycles of development and destruction, either through natural processes or farming machinery (Govers et al., 2007; Poesen, 2018). In contrast, gullies are either impermanent (ephemeral) or permanent channels, larger than rills and characterised by depths >30 cm (Kiani-Harchegani et al., 2021). Gullies in an agricultural setting are often considered permanent if they cannot be easily removed with normal tillage equipment (Posen et al., 2003; McCool and Williams, 2008). Rill and gully development is common on agricultural land in certain regions such as Italy, which possess highly erodible soils and limited vegetation cover and thus they play a critical role in sediment erosion and transport in such regions (Di Stefano et al., 2019; Kiani-Harchegani et al., 2021). However, within the UK rill and gully formation is often limited to a few specific soil types and under certain crop types (e.g., row crops such as potatoes) (Evans et al., 2016; Evans 2017), and therefore typically only occurs in a small number (<10%) of fields per year (Evans et al., 2016). Comparatively, sheetwash has been established to occur extensively and frequently across catchments in the UK, especially in winter months when topsoils are often saturated (Palmer and Smith, 2013; Evans et al., 2016; Pulley and Collins, 2019), even in soils considered at a low risk of erosion (Evans, 2017). Although the quantities of soil particles transported in individual sheetwash events are often small, the high spatial and temporal occurrence of these events can result in substantial delivery of sediments to river systems (Evans, 2017; Pulley and Collins, 2019; Boardman et al., 2020).

1.2.1.1 Controls

Several factors influence rates of erosion and runoff and the transport of fine sediment to river networks. Variations in topography and changes in slope gradients have been demonstrated to exert a strong control on rates of erosion and surface runoff in various regions globally (Morgan, 2009; Fryers, 2013; García-Ruiz et al., 2015), such as on the Loess Plateau, China (Feng et al., 2010; Sun et al., 2014). However, within the UK, only weak relationships between slope and rates of soil erosion and surface runoff have been demonstrated (e.g., Evans and Brazier, 2005; Evans, 2017; Pulley and Collins, 2019). Regional variations in climate can affect the susceptibility of soils to erode and influence spatial and temporal variations in erosion and runoff. For example, regions that have daily mean temperatures <0 °C, often experience winter snow accumulation and then a spring melt and subsequent runoff period, when temperatures increase. Snowmelt has been demonstrated to substantially increase soil erosion and runoff in these regions, for instance, 50-60% of annual fine sediment transport occurred during snowmelt periods in the Central Spanish Pyrenees (Lana-Renault et al., 2011). Similarly, the intensity and volume of rainfall events can alter rates of soil erosion. Higher intensity rainfall events often exhibit larger raindrop sizes, which have greater kinetic energy potential and thus possess a greater capacity to detach sediment particles when hitting the soil. Whereas higher volume of rainfall increases the number of raindrops hitting the soil and therefore, increases the detachment of soil particles (Van Dijk et al., 2002; Legout et al., 2005; Warrington et al., 2009).

Land-use is also a key factor influencing the erodibility of soil and thus rates of erosion and runoff. Permanent vegetation cover provided by forested areas can limit erosion and runoff via a number of mechanisms. These include, canopy interception, which minimises rainfall velocity, limiting its potential to dislodge sediment particles and increased resistance caused by the presence of stems, trunks, and leaves, which in turn reduces flow velocities in runoff (Mohammad and Adam, 2010; Sun et al., 2014). In addition, well-established vegetation root systems can also reduce soil erosion and runoff through a number of mechanisms, including, increased soil stability and increased soil infiltration capacity (Gyssels et al., 2005; Vannoppen et al., 2015). Arable lands often lack continuous vegetation cover, increasing the exposure of bare soil to erosive agents (Wither et al., 2006; Boardman, 2013; Grabowski and Gurnell, 2016; Evans, 2017). This in combination with field operations such as tillage (which disturbs the natural structure and strength of the soil) increases the vulnerability of soil to erosion (Leys et al., 2010; Grabowski and Gurnell, 2016; Govers et al., 2017). These impacts in arable lands are further exacerbated by surface sealing and crusting caused by the redeposition of fine sediment following erosion, which decreases the topsoils water infiltration capacity and thus increases the velocity and volume of overland flow (Leys et al., 2010; Boardman et al., 2020). The influence of heavy farming machinery on the compaction of soils has also been noted to substantially increase the occurrence of widespread saturation-excess overland flow, through reduced infiltration rates (Boardman, 2013; Evans et al., 2016; Evans, 2017; Keller et al., 2019). The vulnerability of arable soils to erosion can also be influenced by the type of planted crop. For example, the close planting and fast growth of oilseed rape minimises the risk of erosion, whereas the greater planting distances and slower growth of maize, increases the risk of erosion (Evans, 2005; Boardman, 2013). Other agricultural land use has also been demonstrated to increase the vulnerability of soil to erosion. Intensive lowland livestock farming on grasslands can cause the compaction, poaching and pugging of soils, subsequently reducing infiltration capacity, and increasing saturation-excess overland flow, and increasing the proportion of bare soils susceptible to erosion (Evans, 1998; Bilotta et al., 2007; Pulley and Collins, 2019). In both arable, pasture and grassland, timing of activities can influence the propensity of soils for erosion and the occurrence of surface runoff. Sediment yields in rivers surrounded by lowland grazing grassland in southwest England, were greater post-ploughing and reseeding in autumn and winter months compared with winters where the fields were left unploughed. This was attributed to the higher occurrence of saturated soils and slower re-establishment of sward cover, prolonging the exposure of bare soils to erosion (Pulley and Collins, 2020). Other changes in land use can also alter soil erosion and runoff. Extensive urbanisation increases the occurrence of impervious surfaces, limiting infiltration rates and increasing surface runoff (Taylor and Owen, 2009).

Land use can also affect field to river channel connectivity in catchments, altering fine sediment delivery pathways and inputs to river networks. Anthropogenic features such as roads, tracks, ditches, and culverts can increase catchment connectivity and thus modify (e.g., accelerate) surface delivery pathways (Evans, 2017; Fuller and Death, 2018; Boardman et al., 2019). Intensive agricultural activities and the use of heavy farming machinery also increase the presence of tramlines and wheelings, further increasing lateral connectivity and surface delivery pathways (Withers et al., 2006; Grabowski and Gurnell, 2016; Boardman et al., 2019). In addition, rill erosion and concentrated flow surface runoff within the UK has been noted to mostly take place down tractor wheelings (Silgram et al., 2010; Evans, 2017). In contrast, barriers to connectivity such as hedgerows, riparian vegetation, and retention ponds, slow or intercept surface runoff and encourage sediment deposition, reducing sediment inputs into river systems (Fryirs, 2013; Grabowski and Gurnell, 2016; Allen et al., 2018; Boardman et al., 2019).

1.2.2 Sediment transport in rivers

Once fine sediment is delivered to river systems, it is transported as either bedload, suspended load, or dissolved load (Knighton, 1998; Hemond and Fechner, 2015). The sand fraction of fine sediment (and sometimes dense organic material; Joyce et al. (2007)), is typically transported as part of the bedload along the channel bed (Hemond and Fechner, 2015; Haschenburger, 2022). These particles are generally in continuous contact with the bed and move via rolling, sliding or in a hopping motion (“saltation”) (van Rijn, 1984; Haschenburger, 2022). The finer fractions of fine sediment, fine-sand, silt, clay, and flocculated material (organic and inorganic) are typically transported in the suspended load (Walling and Moorehead, 1989; Droppo, 2001; Kuhnle, 2013). These particles are carried in suspension above the channel bed by turbulent eddies and generally account for the largest part (80-90%) of the total sediment load (Turowski et al., 2011; Kuhnle, 2013). Materials such as ions (e.g., potassium sulphate, calcium bicarbonate) are transported in solution, known as the dissolved load, and generally do not interact with the riverbed or banks (Navratil et al., 2012; Kuhnle, 2013). However, some fractions of the dissolved load such as soluble reactive phosphorus have been demonstrated to be absorbed into river channel banks (e.g., Tye et al., 2016).

The transport of fine sediment downstream is dependent on the particle (or floc) grain size and the energy of flow velocity (i.e., capacity of the river system to transport sediment) (Brunke, 1999; Kuhnle, 2013; Wilkes et al., 2019). The transport capacity of a river is dependent on its stream power, which is an estimate of the energy of the flowing water per unit length of the systems channel (Bagnold, 1966). A river system’s stream power is calculated on the basis of stream discharge, channel slope and density of the water (Knighton, 1998). Transported fine sediment can be dropped out of suspension and deposited onto the riverbed if the stream power decreases below the required level to transport the sediment, i.e., when the fall velocity of the particle surpasses the turbulence of the flow (Naden, 2010). The fall velocity of a particle is closely related to its size and as such the coarsest particles are often deposited first. However, flocculated particles typically have lower densities and thus have lower settling velocities than mineral grains of the same diameter (Droppo, 2001; 2004). Consequently, the use of effective particle size when establishing settling velocities has been highlighted as more appropriate (e.g., Grabowski et al., 2011; 2012). Reductions in stream power and thus flow velocities and turbulence can occur due to numerous factors including reductions in flow discharge, decreases in channel slope, increases channel width, increases in boundary resistance, obstructions to the flow and separation of the flow (Brunke, 1999; Kuhnle, 2013; Wilkes et al., 2019). Anthropogenic activities have increased the occurrence of these factors; for example, over-abstraction of aquifers for farming and potable supplies can decrease inputs into surface waters in groundwater-dominated systems, such as chalk streams, reducing flows (Bickerton et al., 1993; Petts et al., 1999; Wohl, 2015). In addition, channel modifications (e.g., over-widening for navigation or flood mitigation purposes) and the construction of impoundments (e.g., weirs and dams, for water resource management) can increase water residency periods and decrease water velocities (Bennett et al., 2014; Wohl, 2015; Brown et al., 2018).

1.3 Long-term trends in fine sediment responses

Temporal variations in fine sediment transport ("sediment regime") are determined by the interactions of multiple catchment-scale drivers (Grove et al., 2015), including hydro-meteorological factors, sediment source variations, natural landscape disturbances and anthropogenic activities such as agriculture and urbanisation. Long-term monitoring of suspended sediment fluxes, sediment budgets and the reconstruction of sediment yields from depositional environments (e.g., lakes and reservoirs) have shown a global trend of increasing delivery and transport of fine sediment in river systems. Thus, modern-day sediment yields currently exceed established background levels (Owens et al., 2005; Foster et al., 2011; Collins and Zhang, 2016).

1.3.1 Increases in fine sediment yields

Globally, long-term increases in sediment yields have mostly been attributed to the development and expansion of anthropogenic activities; in particular the introduction and intensification of agriculture and deforestation (Walling, 1999; Owens et al., 2005; Walling, 2006), in a number of phases relating to the rise and fall of civilisations, colonisation and advances in technology, which vary from continent to continent.

1.3.1.1 Pre-industrial revolution

Holocene lake deposits in the UK show several phases of increased fine sediment accumulation, prior to the industrial revolution (Edwards and Whittington, 2001; Chiverrell et al., 2008; Macklin et al., 2010). Firstly, during the Bronze and Romano-British Ages, increases in fine sediment accumulation during these periods corresponded with increased agricultural activities and the development of extensive gullies (Edwards and Whittington, 2001; Lang et al., 2003; Chiverrell et al., 2008). The development of gullies during this period increased catchment connectivity, enabling the remobilisation and transportation of fine sediment deposited on hillslopes due to agriculture during the Neolithic period (Figure 1.3), exacerbating fine sediment accumulation during this period (Lang et al., 2003; Macklin et al., 2014). Secondly, during the Middle Ages (~1000 – 1500 A.D), increases in fine sediment accumulation were synchronous with the agricultural revolution, most notably the uptake of the mould-board plough (Macklin et al., 2010; 2014). This development accelerated agricultural expansion across Northern and Western Europe, as it allowed the exploitation of fertile but heavy clay soils. These phases of fine sediment accumulation and agricultural advances have been observed in other countries across Europe, including the Netherlands (De Moor et al., 2008), Belgium (Rommens et al., 2006; Notebaert et al., 2011), Germany (Lang et al., 2003; Hoffmann et al, 2008), and Spain (Garcia-Ruíz et al., 2020).

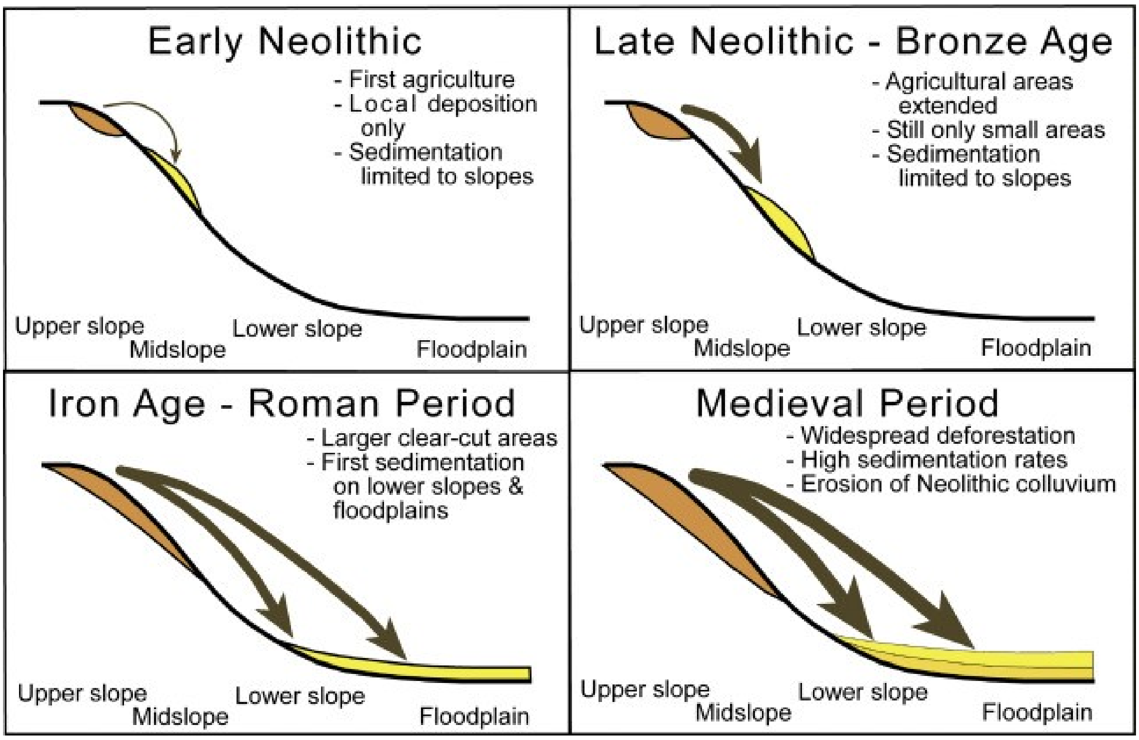


Figure 1.3: Conceptual model of changes in slope-channel coupling from the early to middle agricultural advancement period in Europe (Lang et al., 2003).

Fine sediment accumulations were further compounded during the Medieval period due to anthropogenic alterations of the natural braided and anastomosing channel planforms of rivers across Britain and Europe to single-thread meandering channels, a consequence mostly of land-use changes and the construction of impoundments such as weirs (Lewin, 2010; Brown et al., 2018). Across Europe during the latter half of the 14th century, fine sediment accumulation rates declined due to decreasing erosion and transportation rates. This has been attributed to two factors: reduced precipitation rates and the abandonment and subsequent forest recolonisation of arable land (Lang et al., 2003; Haidvogl, 2018). Decreases in agriculture and abandonment of arable land during this period was a result of declining human populations after the Black Death pandemic, although the extent of population declines and decreases in agricultural land extent varied substantially at regional scale (Yeloff and van Gee, 2007; Izdebski et al., 2022). Between the 15th and 18th centuries, fine sediment accumulation rates steadied across certain areas of Europe, such as Germany; this has been linked to agriculture land abandonment and lack of cumulative extreme rainfall events. The subsequent increases in forested areas, also protected surface soils from runoff and erosion, limiting fine sediment inputs into river systems (Lang et al., 2003; Dotterweich, 2008). Whereas other regions saw intensification of cereal agriculture and grazing during this period (such as Spain) increasing erosion rates and sedimentation (Garcia-Ruiz, 2010; Bellin et al., 2013).

1.3.1.2 19th Century onwards

The industrial revolution in Europe during the 19th century, saw extensive damming of river systems to exploit waterpower; this had substantial influence on the transport capacity of fluvial systems, and increased sediment storage in river channels (Brown et al., 2018). European river systems have since seen two phases of increased sedimentation since the start of the 20th century; pre-1950s and post-1950s, representing a shift from increases in areas of agricultural land to increases in the intensity of agricultural practices (Vanwallegham et al., 2011; Foucher et al., 2014; Grabowski and Gurnell, 2016). Accelerated sedimentation post-1950s has been attributed to the increases in bare, tilled soils that are highly susceptible to erosion, a consequence of the shift from low intensity farmland to cultivated, high intensity crop-land (Boardman, 2003; Collins and Walling, 2007a; Johannsen and Armitage, 2010; Grabowski and Gurnell, 2016; Evans, 2017). In addition, the amalgamation of smaller fields into larger ones and the removal of hedgerows and riparian vegetation have increased runoff pathways and catchment-river connectivity, further accelerating sedimentation (Lang et al., 2003; Boardman, 2013; Grabowski and Gurnell, 2016; Evans, 2017; Boardman et al., 2019). These impacts have been compounded by the introduction of heavier farming equipment, which increased surface runoff and thus fine sediment inputs, through increased soil compaction and decreased infiltration (Bilotta et al., 2007; Vanwallegham et al., 2011; Evans, 2017). Such alterations to land use and agricultural intensity have been observed across Europe since the 1950s contributing to the substantial increases in sedimentation rates, including in Germany (Lang et al., 2003), Belgium (Rommens et al., 2006), and Spain (Vanwallegham et al., 2011). For instance, since the 1950s 93% of low intensity grassland in lowland France has been converted to high intensity winter and spring crops and individual arable plot size has increased on average by 465% (Foucher et al., 2021). This resulted in increased sediment accumulation in waterbodies from 40 t y^{-1} before the 1950s to 90 – 102 t y^{-1} between 2003 and 2013 (Foucher et al., 2014). Despite this change in lowland land-use, most European upland land-use practices have remained relativity unchanged during the 20th century. Subsequently, increases in sedimentation in upland systems has been attributed to global climate change (Rose et al., 2011). Elevated winter rainfall frequency and intensity, combined with prolonged periods of summer drought, have increased the susceptibility of upland soils to erosion, thus increasing fine sediment inputs to river systems (Guilizzoni et al., 2006).

Accelerated erosion and sedimentation since the 19th century has also been observed elsewhere globally. The rapid introduction of the European style of agriculture and deforestation by European settlers in North America, drastically accelerated erosion and runoff, due to the formation of rills and intensive gullying on slopes (Brierley et al., 2005; Dotterwich et al., 2014; Dietz et al., 2015). This resulted in marked accumulation of fine sediment i.e., sediment quantities that had taken 300 years to accumulate previously, took only 80 years to accumulate over the late 19th and early 20th centuries (Dotterwich et al., 2014). Similarly, to Europe, sedimentation rates in the USA have further accelerated in the 20th century, most notably since the 1950s, this has also been attributed to increases in agricultural intensification (Jones and Schilling, 2011; Heathcote et al., 2013), with total agricultural land area remining relatively unchanged since the early 1900s (Heathcote et al., 2013). Similar trends in sediment yields since the 1950s have also been observed in Canada, also due to the intensification of land-use activities; specifically, forestry activities, including timber harvesting and associated increases in road densities (Schiefer et al., 2013). Deforestation reduces precipitation interception by vegetation, increasing surface runoff and thus stream discharges (Hotta et al., 2007; Cotel et al., 2020). In contrast, certain regions have only seen increases in suspended sediment loads and fine sediment accumulation over the last few centuries. Australian river systems, prior to European settlers in the late 19th century, exhibited relatively unaltered sediment regimes due mostly to a lack of agricultural practices by Indigenous people. However, the introduction of advanced agricultural technology and land clearance by European settlers substantially increased fine sediment erosion and accumulation (Verstraeten and Prosser, 2008; Kemp et al., 2015). The extensive rill and gully development, as a result of introduced intensive agricultural practices and relativity undisturbed soils, drastically increased erosion, and runoff pathways (Saxton et al., 2012; Shellberg et al., 2016). Consequently, suspended sediment loads increased by a factor of more than 150 compared with pre-European settlement (Verstraeten and Prosser, 2008; Shellberg et al., 2016).

1.3.2 Decreases in fine sediment yields

The observed increases in fine sediment delivery and sedimentation in river systems globally have not always translated to increased overall sediment yields (Owens et al., 2005). Changes in sediment storage within systems and the construction of impoundments such as dams has caused some suspended sediment yields to remain constant or even decrease in recent decades (Walling and Fang, 2003; Dang et al., 2010; Yang et al., 2015). Syvitski et al. (2022) estimated that sediment yields globally would have increased by an additional 212% between 1950 and 2010, if it were not for sediment sequestration by dams. In Brazil, for example, the construction of the Sobradinho Dam in 1978 reduced the annual suspended sediment load output from the São Francisco River by approximately 80%, from 11 Mt y^{-1} to 2 Mt y^{-1} (Walling, 2006). Conversely, some river systems have exhibited a decrease in suspended sediment yields in recent years, not associated with the construction of impoundments, but as a result of soil conservation efforts and attempts to reverse the impacts of intensive agricultural techniques of the 20th century (Meade and Moody, 2010). For instance, the average suspended sediment yields of various Italian river systems have almost halved in the 1990-2019 period (98 tkm^{-2} yr^{-1}) compared with the 1956-1984 period (206 tkm^{-2} yr^{-1}) (Billi and Spalevic, 2022). This observation has been suggested to be a consequence of a combination of decreasing annual rainfall amounts, and subsequent decreases in river discharges, and of land-use changes in the region, in particular the increase in forested areas. Forested areas in Italy increased by 20% between 1985 and 2005, and by 2018 approximately 40% of the total area of the Italian territory was covered by forests, exceeding the area covered by agriculture (Marchetti et al., 2018).

1.3.3 Future changes in sediment yields

The frequency and intensity of extreme rainfall events are predicted to increase under current projections of future climate change (Zhu, 2013; Jones et al., 2014; Yilmaz et al., 2014). Soil erosion is expected to be directly impacted by these predicted changes in precipitation, including rainfall quantities, spatiotemporal distributions, and intensity (Wilby et al., 2010; Li and Fang, 2016). For example, increases in rainfall intensity during winter months, when soils are more likely to be saturated, is predicted to increase soil erosion and runoff through lower infiltration and increased splash erosion, thus increasing sediment inputs to river systems (Zhang and Nearing, 2005; Serpa et al., 2015; Bussi et al., 2016). It has also been suggested that reductions in solar radiation caused by prolonged rainfall periods also has the potential to limit plant growth, resulting in less vegetation cover and less raindrop interception, thus increasing soil erosion through increased detachment (Wang et al., 2015). Furthermore, drought conditions and low flow occurrences are expected to increase as a result of longer, hotter, and drier summers. This situation is predicted to increase sedimentation due to reductions in the transport capacity of systems, promoting fine sediment deposition (Dewson et al., 2007). The impacts of this are expected to be greater in river systems that already experience low flow conditions during summer months, such as groundwater-dominated systems, including chalk streams (Allen and Crane, 2019; Stubbington et al., 2022). The predicted shorter, more intense winter rainfall periods, which end earlier in the year have the potential to reduce the periods of groundwater recharge, further exacerbating low flow conditions in chalk streams (Allen and Crane, 2019; Stubbington et al., 2022).

In addition to changes to hydro-meteorological conditions due to climate change, alterations to land-use are likely to continue to take place in the future as the demands on resources shift. The continuing increases in global food demands (Godfray et al., 2010; Foley et al., 2011), mean that the need for more resources will result in the increased demand to develop more agricultural land (Ray et al., 2013; Jacobson et al., 2019). In addition, the use of corn for biofuels is further increasing the pressure to convert additional land into agriculture for food production (Lark et al., 2015). Increases in the area of land used for agriculture are likely to accelerate sedimentation, however, there has been increasing recognition in recent years of the need for soil conservation practices to minimise the erosion and runoff of soil from agricultural land such as alterations to traditional tillage practices (Leys et al., 2010; Busari et al., 2015). Predictions of the extent and magnitude of soil erosion and sedimentation due to land-use change and climate change vary substantially, depending on the models and climate projections used (Bussi et al., 2016; Wild et al., 2023). For example, Stern et al., (2020) predicted that by the end of the century, suspended sediment loads in the Sacramento River Basin (Northern California) will increase by 39% under Representative Concentration Pathway (RCP) 4.5

(2.4 °C increase in global temperatures) but increases to +69% under RCP 8.5 (4.3 °C increase in global temperatures).

1.4 Impacts of elevated levels of fine sediment

1.4.1 Physical impacts

Elevated fine sediment loads in river systems can have a number of detrimental impacts. For instance, elevated suspended sediments and associated contaminants can result in increased water treatment costs for drinking water (Hilton et al., 2006; Vörösmarty et al., 2010). Whereas, elevated rates of fine sediment accumulation can reduce the channel capacity, increasing potential flood risk, especially during the winter months when the occurrence and intensity of rainfall events are higher (Wheater and Evans, 2009). In addition, elevated fine sediment accumulation in reservoirs can reduce the storage capacity and therefore affect water supplies for both farming and potable supplies and potentially increase the need for costly dredging activities (Kondolf et al., 2014; Morris, 2020).

Elevated deposition and infiltration of fine sediment into riverbed frameworks ("colmation") blocks the interstitial pore spaces and reduces intra-gravel permeability and porosity. As a result, intra-gravel flows and dissolved oxygen concentrations are reduced (Veličković, 2005; Sear et al., 2008; Grischek and Bartak, 2016; Fetzer et al., 2017; Wharton et al., 2017). In addition, the colmation of riverbed frameworks can have negative implications for groundwater-dominated river systems, such as chalk streams, through reductions in hydraulic connectivity. This subsequently limits the spatial and temporal patterns of water exchange, dissolved substances, dissolved oxygen, and fine sediment exchange between the surface and benthic substrates and the underlying hyporheic zone and groundwater (Boulton et al., 1998; Brunke, 1999; Krause et al., 2009; Wharton et al., 2017). In extreme circumstances, the hyporheic zone becomes in essence, disconnected from the benthic substrates (Hartwig and Borchardt, 2015; Mathers et al., 2019).

1.4.2 Ecological impacts

The detrimental impacts of elevated fine sediment loads in river systems on freshwater organisms has been well-established and has been attributed to both elevated suspended fine sediment concentrations in the water column and elevated rates of fine sediment deposition, infiltration, and accumulation in riverbed frameworks (Figure 1.4).

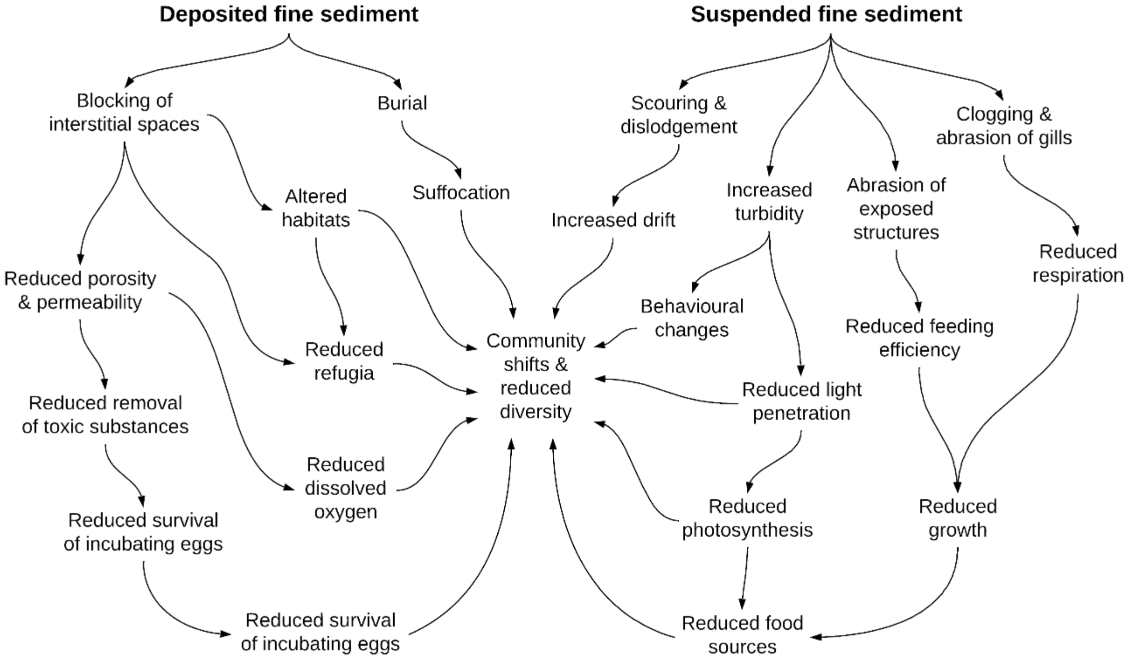


Figure 1.4: Conceptual diagram of the impacts of elevated fine sediment inputs into river systems on freshwater organisms, detailing both the impacts associated with suspended fine sediment and accumulation of fine sediment within riverbeds.

1.4.2.1 Suspended fine sediment

Elevated fine sediment concentrations in the water column of river systems have been demonstrated to have a number of direct impacts on the functioning of various freshwater organisms, including abrasion damage, burial and sediment build-up on exposed body parts (e.g., gills, filter-feeder apparatus, macrophyte stands and leaves) (Barko and Smart, 1986; Wood et al., 2005; Robertson et al., 2006; Bilotta and Brazier, 2008; Conroy et al., 2018; McKenzie et al., 2020). The inflicted damage can have further consequences for freshwater organisms. Fine sediment induced gill damage, for instance, has been shown to have a range of negative impacts on fish and invertebrates, including, decreased growth rates in minnows (*Cyprinella galactura* and *Erimonax monachus*) (Sutherland and Meyer, 2007), reductions in aerobic scope in white-clawed crayfish (*Austropotamobius pallipes* L.) and signal crayfish (*Pacifastacus leniusculus* D.) (Rosewarne et al., 2014) and reduced oxygen uptake in three species of eastern shiners (*Notropis*) (Gray et al., 2016).

Elevated suspended fine sediment concentrations are known to increase turbidity in the water column, which has a number of indirect consequences for freshwater organisms. Increases in turbidity can limit light penetration into the water column, which can reduce photosynthesis by aquatic macrophytes and phytobenthos, affecting their primary production and influencing dissolved oxygen concentrations (Barko and Smart, 1986; Wood and Armitage, 1997; Robertson et al., 2006; Kjelland et al., 2015). Increased suspended sediment concentrations and turbidity have also been demonstrated to induce behavioural changes in freshwater organisms, such as increased macroinvertebrate drift (Gibbins et al., 2007a; 2007b; Béjar et al., 2017). This has been attributed to both the abrasion of suspended particles dislodging individuals, and responses to changes in light conditions, darker environments often being associated with safer areas for redistribution (Gibbins et al., 2007a; 2007b; Béjar et al., 2017). Behavioural and physical impacts due to increased turbidity have also been observed in fish species, such as reductions in swimming performance in Brown trout (*Salmo trutta* L.) (Berli et al., 2014), increased stress hormone (cortisol levels) in ayu (*Plecoglossus altivelis*) (Awata et al., 2011) and shifts to more opportunistic feeding groups (Sullivan and Watzin, 2010).

1.4.2.2 Fine sediment accumulation in riverbeds

The accumulation of elevated fine sediment in riverbed frameworks often results in a more homogenous benthic habitat and limits available intra-gravel pore space. This, in combination with reductions in intra-gravel flows and dissolved oxygen concentrations, has been demonstrated to have negative implications for freshwater communities such as decreases in species diversity and shifts in community assemblages (Rabení et al., 2005; Bo et al., 2007; Murphy et al., 2017). For example, altered macroinvertebrate communities are characterised by species more tolerant to high rates of fine sediment accumulation (e.g., small body sizes and short life cycles) and/or specific traits (e.g., burrowing or tegumental respiration, respiration through the body surface) (Larsen et al., 2009; 2011; Descloux et al., 2013; 2014; Mathers et al., 2017; 2019). Similar shifts in diatom assemblages towards those more tolerant of elevated fine sediment accumulation have also been observed, resulting in a higher abundance of larger motile species, and thus allowing species to remain on the surface of sediment deposits and to ensure light availability (Piggott et al., 2012; Neif et al., 2017). Reductions in dissolved oxygen concentrations within riverbeds can also increase stress in aquatic macrophytes and result in the shift from submergent to emergent species, reducing species diversity (Bornette and Puijalon, 2011). Additionally, the clogging of interstitial spaces can increase barriers to freshwater organism movement within riverbed frameworks, such as decreased vertical movement of freshwater amphipods (*Gammarus pulex*) (Mathers et al., 2019; Vadher et al., 2022). This can also reduce access to refugia in the sub-surface during the drying of river systems and re-emergence once surface flows resume. This is likely to become an increasing problem as more river systems dry out and prolonged drying periods occur, due to increased temperatures, changes in precipitation regimes and alterations in aquifer recharge periods, due to climate change (Vadher et al., 2022).

Elevated fine sediment accumulation in riverbed frameworks can also have detrimental impacts on certain life-cycle stages of freshwater organisms. The impacts of this on the development and recruitment of incubating salmonid eggs and emerging alevins has been well-established (e.g., Greig et al., 2007; Sear et al., 2008; Levasseur et al., 2011; Pattison et al., 2014; Bloomer et al., 2016; Sear et al., 2016). Various processes have been described to explain the observed implications, in particular, reductions in the availability of dissolved oxygen. A sufficient supply of dissolved oxygen is required to drive diffuse oxygen exchange across the egg membrane and enable successful incubation (Greig et al., 2005a; 2007). However, the accumulation of fine sediment within riverbeds limits the passage of oxygenated flows via the blocking of intra-gravel pore spaces and reductions in interstitial flow velocities (Acornley and Sear, 1999; Greig et al., 2005a; 2007; Levasseur et al., 2011; Pattison et al., 2014). In addition, clay-sized particles (<4 μm) have been demonstrated to directly block chorin micropores in egg membranes, preventing oxygen diffusion and metabolic waste removal (Greig et al., 2005b), further limiting diffuse oxygen exchange. Fine sediment associated organic matter also reduces dissolved oxygen concentrations via oxygen consumption during its decomposition (Collins et al., 2014; Sear et al., 2016; 2017).

Other impacts of fine sediment accumulation on incubating salmonid eggs, aside from its impacts on dissolved oxygen concentrations, have also been noted. This includes the blocking of interstitial pore throats by coarser fine sediment particles which results in the asphyxiation and entombment of the emerging salmonid alevins (Acornley and Sear, 1999; Sear et al., 2016). Despite these observed impacts on salmonid progeny, there has been limited focus on the implications for non-salmonid fish, even though 85% of lithophilic fishes in Europe are non-salmonids (Bašić et al., 2019) and that multiple species (e.g., cyprinids) require similar spawning habitats. The detrimental implications that have been observed for non-salmonid species include reducing incubating egg survival for Dace (*Leuciscus leuciscus* L.) (Mills, 1981), premature emergence for European barbel (*Barbus*

barbus L.) (Bašić et al., 2019) and reduced emergence success and larvae size for European nase (*Chondrostoma nasus* L.) (Duerregger et al., 2018; Nagel et al., 2020). In addition, Everall et al., (2018) demonstrated increased incubating egg mortality in mayflies (*Serratella ignita* P.) due to suffocation and dislodgement caused by elevated fine sediment accumulation.

1.4.3 Sediment associated pollution

Fine sediment has been demonstrated to have a high affinity for soluble metals, pesticides, and organic contaminants. Sediment-associated metals from mining activities can have a wide range of detrimental impacts for freshwater organisms, including reduced invertebrate species richness, increased fish mortality and reduced spawning and recruitment success (especially for salmonids) and reduced diversity in diatom and aquatic macrophyte assemblages (Ivorra et al., 2002; Auladell, and Sadler, 2010; Qu et al., 2010; Bere et al., 2016; Jones et al., 2016). Fine sediment in rivers can also act as a dispersal agent for microplastics (Horton et al., 2017; Hurley et al., 2018; He et al., 2021), with the negative physical and ecological implications of microplastics in river systems of increasing concern (Hurley et al., 2018; Parker et al., 2021). Sources of microplastics include, sewage effluent, road runoff, agricultural fertilisers, and fragmented agricultural plastics (Horton et al., 2017). The ingestion of microplastics by fish can result in detrimental impacts via a number of mechanisms. Firstly, the physical effects of microplastic such as blocking of the gastrointestinal tract. Secondly, the leaching of plasticisers and other harmful chemicals from the microplastic. Thirdly, the desorption of harmful contaminants bound to the microplastics (Strungaru et al., 2019; Parker et al., 2021). The detrimental impacts of these mechanisms on fish species include changes in feeding rates, alterations gene expression and development and/or reductions in survival rates (Jovanović, 2017; Wang et al., 2020; Parker et al., 2021).

Fine sediment also plays an important role in the transport of nutrients such as nitrogen and phosphorus (P) in river systems (Walling et al., 1997; Warren et al., 2003). Substantial proportions (26-78%) of annual total P loads in several UK rivers have been identified to be transported in association with fine sediment (i.e., particulate P) (Withers et al., 1998; Walling and Collins, 2005). Elevated particulate and dissolved phosphorus (P) can enter river systems from diffuse sources (e.g., agricultural land and channel banks) (Zhang et al., 2014; Pulley et al., 2022) and from point sources (e.g., sewage treatment works and industrial wastewaters) (Bowes et al., 2008). In UK agricultural catchments

43% of flux particulate phosphorus (PP) was identified as originating from channel banks or subsurface source erosion (Walling and Collins, 2008; Walling et al., 2008). In addition to increased loads of sediment-associated nutrients due to anthropogenic activities, channel modifications and impoundments such as weirs can promote long-term nutrient retention (e.g., PP), via decreases in flow heterogenicity and increased water residency times, promoting sedimentation (Withers and Jarvie, 2008). Elevated inputs of nutrients into river systems can result in substantial detrimental impacts for freshwater systems and organisms they support. Elevated inputs of nitrogen and phosphorus can cause an increase in plant biomass i.e., increases in primary production (Mainstone and Parr, 2002; Hilton et al., 2006). Increases in nutrient inputs can also cause shifts to more nutrient-tolerant species and a shift from macrophyte to benthic, filamentous, or planktonic algal dominated assemblages (Hilton et al., 2006). The establishment of dense surface plant biomass can also occur, resulting in increased shading of the water column and bacterial degradation of excessive amounts of organic material, increasing the potential for anoxic conditions, which can have substantial ecological impacts (Zhang et al., 2017b; Riley et al., 2018). In addition, these conditions can increase water treatment costs (Vörösmarty et al., 2010).

1.5 Chalk streams

Chalk streams are a relatively rare river systems globally, only occurring within the UK, France, Belgium, and New Zealand (Environment Agency, 2004). Most of these river systems occur in the UK (85%), within the SW-NE chalk outcrop (O’Neill and Hughes, 2014; Figure 1.5). Chalk streams are defined as groundwater-dominated systems, with a base-flow index (flow derived from groundwater aquifers) exceeding 75% and a course which runs predominantly over chalk geology. Subsequently, approximately 90% of their annual discharge arises from groundwater sources (Mainstone, 1999). As a consequence of their groundwater-dominated flows, chalk streams are characterised by stable yet distinctive seasonal flow regimes that are less responsive to storm-runoff compared with river systems on impermeable geology (Heywood and Walling, 2003; Grapes et al., 2005; Sear et al., 2006). These flow regimes give rise to distinctive characteristics including, high width to depth ratios, low slopes, low rates of active bank erosion and limited catchment to river connectivity (Sear et al., 1999; Whiting and Moog, 2001; Heywood and Walling, 2003). The occurrence of sinuous planforms in chalk streams contradict these characteristics and thus, are likely a result of past hydrological conditions. Substantial fine sediment accumulation during the Holocene fossilised the highly braided and meandering high energy lowland river systems formed in the last glacial period (Collins et al., 2006; Brown et al., 2018; Whiteman and Haggart, 2018). The sinuous planforms and relatively immobile fluvial gravel beds of chalk streams suggests that their gravel beds are fossils, remnants that developed under higher energy conditions (Sear et al., 2006).

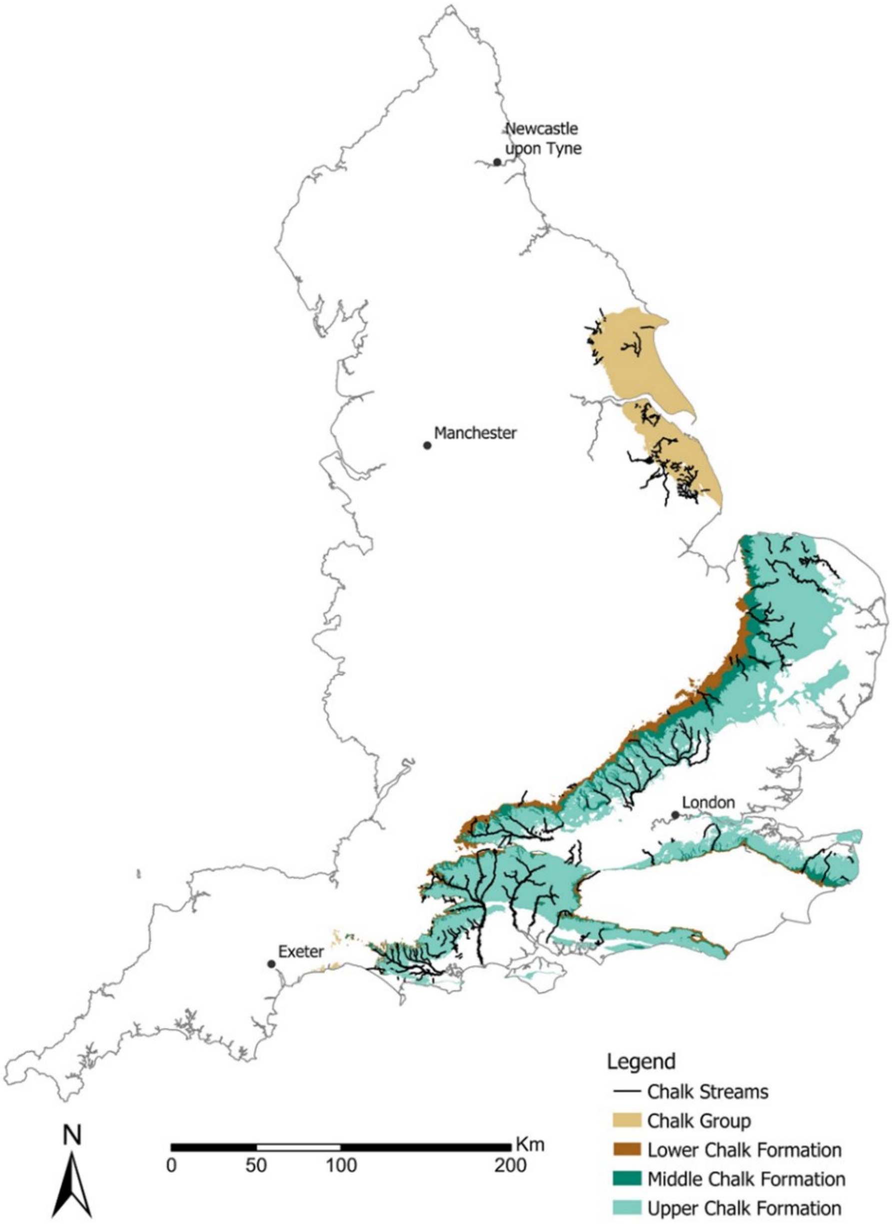


Figure 1.5: The location of chalk streams within the SW-NE chalk outcrop in England (Data accessed: British Geological Survey, 2008; Ordnance Survey, 2020).

Subsequently, in their unmodified channel form, chalk streams have a low or even an absence of sediment available for transport. As a result, background concentrations of suspended fine sediment in chalk streams are substantially lower compared with other river systems in the UK (e.g., <5 t km^{-2} year^{-1} compared with > 100 t km^{-2} year^{-1}) (Acornley and Sear, 1999; Heywood and Walling, 2003; Cooper et al., 2008). Low suspended sediment concentrations in combination with the characteristic lack of available energy for bedload transport, due to low stream power and concretion of bed substrates by calcareous deposits (tufa) means that chalk streams should naturally lack elevated fine sediment storage (Acornley and Sear, 1999; Sear et al., 1999; 2006; 2010). Consequently, the naturally clear waters and clean gravel bed of chalk streams create the ideal habitats for numerous nationally and internationally (European) protected species, including, Atlantic salmon (*Salmo salar* L.), white-clawed crayfish (*A. pallipes* L.) and stream water-crowfoot (*Ranunculus penicillatus subsp. pseudofluitans)* (Mainstone, 1999)

1.5.1 Human influence

Chalk streams have been heavily influenced by anthropogenic activities and modifications for centuries, subsequently altered the hydrological and sedimentological processes in chalk streams and affected their response to elevated fine sediment loads.

1.5.1.1 Channel and catchment modifications

Chalk streams have experienced alterations and modifications to their channels and catchments similar to most river systems in the UK (and Europe) have been exposed to since the Neolithic period (Brown et al., 2018). Forest clearance for agriculture in chalk stream catchments started with small-scale clearings during the Neolithic period and by the Middle Bronze Ages had developed into large-scale clearings. Localised areas of forest clearance for agriculture in chalk stream catchments continued throughout the Roman period, peaking in the Middle Ages, when extensive forest clearance occurred (Green, 2000). The construction of impoundments such as weirs and water mills for power-generation and flour production, in chalk stream channels was extensive during the late Roman period and Middle Ages (Watts, 2002). Also, the construction of water mills often involved the creation of multiple man-made channels, in order to utilise power-generation continuously (Berrie, 1992; Langdon, 2004). Although the intended use of these impoundments and artificial channels reduced drastically during the 19th and 20th centuries, due to advances in technology, many of the original structures persist today in chalk streams and continue to alter hydrological conditions.

Several anthropogenic activities and modifications were more unique to chalk stream catchments. For instance, water meadows were widely established in southern and some eastern chalk stream catchments throughout the 17th and 18th centuries (Martins and

Williamson, 1994; Historic England, 2017). These artificial irrigation systems were mostly constructed in the downstream floodplain reaches of chalk streams, although did also occur along the headwaters and winterbourne reaches of many chalk streams (Martins and Williamson, 1994; Mainstone, 1999; Historic England, 2017). The establishment of water meadows resulted in the stabilisation and straightening of many chalk stream channels and the construction of numerous impoundments and artificial channels. Despite the majority of water meadows being abandoned or converted to high intensity agriculture during the 20th century, most of the relict features (e.g., artificial channels, sluices, and hatchways) persist and continue to alter the channel planforms and hydrological conditions in chalk streams (Mainstone, 1999; Historic England, 2017). In addition, chalk aquifers have been over-abstracted for farming and potable supplies since the early 20th century. Over-abstraction of the chalk aquifers reduces groundwater inputs into chalk streams and consequently, reduces discharges and flow velocities, especially in drought years (Bickerton et al., 1993; Wood and Petts, 1999; House and Punchard, 2007). Extensive watercress and fish farming in the headwaters of many chalk streams since the 19th century, especially in southern England (i.e., Hampshire and Dorset chalk streams), have also contributed to the over-abstraction of chalk aquifers (Smith, 1992; Casey and Smith, 1994). These alterations to channel planforms, construction of impoundments and over-abstraction of groundwater sources, have all contributed to reduced groundwater inputs and homogenised flow conditions, thus reducing flow velocities in chalk streams. Consequently, compounding the low bed mobilising flows characteristic of chalk streams, further limiting sediment transport, and increasing fine sediment deposition and accumulation within their gravel beds.

1.5.1.2 Increases in fine sediment inputs

In chalk stream catchments, the intensification of agriculture since the 1940s has been drastic, in particular this has included the shift from predominantly low intensity farming and pasture to high intensity autumn-sown winter cereal cultivation (Boardman, 2003; Collins and Walling, 2007a; Grabowski and Gurnell, 2016; Evans, 2017), e.g., the observed increases in wheat and barley crops in Dorset chalk stream catchments over this time period (Figure 1.6). The shift to autumn-sown winter crops has increased the proportion of exposed bare, tilled soils that are highly susceptible to erosion (Grabowski and Gurnell, 2016; Boardman, 2020). Importantly, the concurrent ploughing and reseeding of over-wintering crops during the autumn months when topsoils are often saturated and the high occurrence of high intensity rainfall events, increases the potential for saturated-overland flow and thus, has increased sediment delivery to chalk streams (Palmer and Smith, 2013; Evans et al., 2016; Pulley and Collins, 2019). For example, in the River Wissey (a chalk stream in Norfolk, UK) catchment, the majority of severe erosion events took place during the winter months, attributed to thinly crop covered soils, saturated topsoils and bare tractor wheelings in fields drilled in autumn and harvesting of potatoes and sugar beets, resulting in rutted bare fields (Evans, 2017).

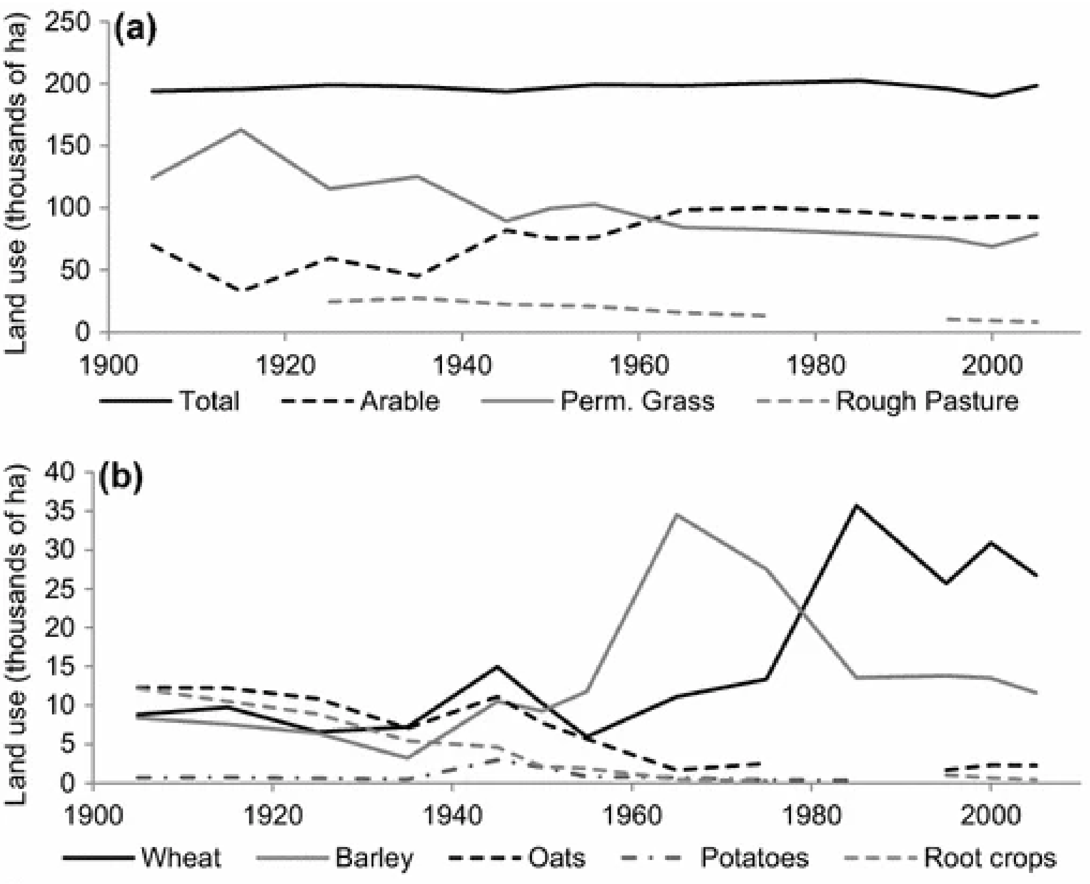


Figure 1.6: Changes in agricultural land-use in chalk stream catchments (Dorset, UK) during the 20th century; (A) area of land under different agricultural land use types and (B) area of arable land under different crop types (Grabowski and Gurnell, 2016).

There has also been a shift from predominantly sheep grazing to predominantly cattle grazing in chalk stream catchments since the 1940s (Grabowski and Gurnell, 2016; Evans, 2017), this has increased fine sediment inputs into river channels via several mechanisms. Firstly, the trampling of soils by cattle causes soil compaction, poaching and pugging, which reduces the soils infiltration capacity, increasing the occurrence of saturation-excess overland flow (Evans, 1998; Bilotta et al., 2007; Pulley and Collins, 2019). Secondly, cattle access to river channels can destabilise riverbanks, causing bank slumping and/or collapse, resulting in an increase in fine sediment inputs (Bond, 2012). The poaching of river banks by cattle has also been shown to increase chalk stream channel widths, decreasing flow velocities and promoting fine sediment deposition and accumulation (Acreman and Dunbar, 2010). The impacts of cattle access to river channels are potentially greater in chalk streams compared with other river systems given the naturally low rates of bank erosion. Agricultural intensification in chalk stream catchments has also increased surface delivery pathways and thus, fine sediment inputs to river channels, through the amalgamation of smaller fields into larger ones and subsequent, removal of hedgerows in chalk stream catchments (Boardman, 2013; Grabowski and Gurnell, 2016; Evans, 2017; Boardman et al., 2019). In addition, the introduction of heavy farming machinery has increased soil compaction, especially along tramlines and wheelings, further increasing surface delivery pathways and thus, increasing fine sediment inputs to chalk stream channels (Withers et al., 2007; Boardman et al., 2019; Boardman, 2020). The naturally low catchment-to-river connectivity in chalk stream catchments, resulting from their groundwater-dominated flows, suggests that the associated impacts of increased catchment connectivity are potentially greater in chalk streams compared with other UK river systems (Boardman, 2003; 2013; Evans, 2017).

The presence of watercress farms in the headwaters of many chalk streams (especially in southern England) have also been identified as a source of elevated fine sediment inputs (e.g., Smith, 1992; Casey and Smith, 1994; Zhang and Collins, 2017; White, 2020). Elevated suspended sediment loads from watercress farms have been attributed to “salad wash” effluents (often discharged daily during summer months) and activities such as bed cleaning and harvesting (generally occurs multiple times a year) (Cotter, 2012; White, 2020). Other anthropogenic activities have also been identified as contributing to elevated fine sediment loads in chalk streams including septic tanks, fish farms, sewage treatment plant effluent, and damaged road verges (Casey and Smith, 1994; Neal et al., 2000; Collins et al., 2010; Zhang and Collins, 2017).

1.5.2 The fine sediment problem

Despite relatively low suspended sediment concentrations, fine sediment has been highlighted as a key factor contributing to chalk stream degradation and the habitats they provide, with only 16.7% of chalk streams in the UK being classified as in “good ecological status” or higher under the Water Framework Directive (WFD) (Environment Agency, 2020). Chalk stream gravel beds regularly exhibit higher quantities of accumulated fine sediment compared with other gravel bed river systems in the UK (Acornley and Sear, 1999; Milan et al., 2000; Sear et al., 2008). This has been attributed to the propensity of chalk stream gravel beds to accumulate fine sediment. A consequence of their natural hydrological conditions, in particular their inability to remobilise deposited fine sediment due to low bed mobilising flows, resulting from their groundwater-dominated flows, and resulting stability of the gravel beds (Acornley and Sear, 1999; Sear et al., 1999; 2005). The characteristic low bed mobilising flows of chalk streams have been compounded by centuries of anthropogenic activities (such as over-abstraction) and modifications to channel planforms (e.g., weirs and channel straightening), which have reduced flow velocities, increasing fine sediment deposition and accumulation. Elevated fine sediment inputs from the intensification of agriculture in chalk stream catchments and other anthropogenic activities, have further increased quantities of accumulated fine sediment. Numerous immobile critical life-cycle stages of chalk stream biota (such as incubating lithophilic eggs and benthic invertebrates) are highly sensitive to elevated fine sediment loads (e.g., Greig et al., 2005a; Sear et al., 2016; Everall et al., 2018; Bašić et al., 2019) and subsequently, coupled with the propensity of chalk stream gravel beds to accumulate fine sediment, has resulted in the high potential for long-lasting lethal/sub-lethal ecological impacts in chalk streams.

1.6 Challenges for fine sediment management

The increases in fine sediment inputs into chalk streams, especially since the intensification of agriculture in the 1940s, combined with the detrimental ecological impacts associated with these elevated fine sediment loads, has increased the recognition for the need to manage fine sediment in river systems.

1.6.1 Sediment targets

Numerous sediment targets have previously been established and proposed, they can be split into two distinctive groups: water column metrics and river substrate metrics Water column metrics include: turbidity, light penetration and suspended sediment concentration statistics and river substrate metrics include: riffle stability and embeddedness/substrate composition (Collins et al., 2011; Collins and Pulley, 2016). However, these targets have in the past often failed to provide a scientifically- based and robust baseline for effective and successful management in river systems (Walling et al., 2007; Collins et al., 2011); as such river systems continue to be negatively impacted by excessive fine sediment. This failure has been attributed to a number of assumptions that underpin these targets and the resultant management.

1.6.1.1 Threshold-based targets

Many existing targets are related to critical sediment concentration thresholds. One such example of a water column threshold target is the now repealed EU Freshwater Fish Directive (FFD) (78/659/EC) target for annual mean suspended sediment concentration (25 mg L^{-1}) (Collins and Anthony, 2008). The FFD was repealed in 2013 and overtaken by the WFD. Despite, identifying suspended fine sediment (critically, both the inorganic and organic fractions) as a pollutant of concern, contributing to the failure of waterbodies to achieve "good ecological" status, the WFD fails to state an explicit target for fine sediment (Cooper et al., 2008; Grove et al., 2015; Collins and Zhang, 2016). The lack of a replacement target in the WFD means that most member states still rely on the repealed target as set within the FFD. Regardless, these threshold targets are underpinned by a number of assumption and failings, particularly, the assumption that there is a direct and linear concentration- ecological dose-response to fine sediment, whereby increasing concentrations of fine sediment are assumed to result in increasing detrimental ecological impacts. Numerous studies have demonstrated that this is not always the case, with adverse ecological impacts being observed at relatively low suspended sediment concentrations, due to the interplay of additional factors including, proportion of organic content, timing of delivery, length of exposure and affected species life-cycle stage (Greig et al., 2007; Sear et al., 2016; Bašić et al., 2019).

Additionally, the use of a single annual "one-size-fits-all" suspended sediment target is often inappropriate, given the natural differences in geomorphological processes between river system types and thus their intrinsic variations in suspended sediment concentrations. For instance, analysis of suspended sediment concentrations from 42 different river system types in the UK identified a 15-fold difference in the background suspended sediment concentrations (Bilotta et al., 2012). It was also noted that 78% of the river systems exhibited mean suspended sediment concentrations of <12.5 mg L^{-1} (Bilotta et al., 2012). These suspended sediment concentrations were less than half that of the FFD target (25 mg L^{-1}), indicating that, for the majority of river systems in the UK, this suspended sediment target is too high. Annual suspended sediment yields in chalk streams (<5 t km^{-2} $year^{-1}$) are also substantially lower than suspended sediment yields in other UK river systems (>100 t km^{-2} $year^{-1}$) (Heywood and Walling, 2003; Walling et al., 2007), further highlighting that the use of single suspended sediment concentration target for all river systems are inappropriate, especially with respect to chalk streams.

1.6.1.2 Regime-based targets

Numerical threshold targets such as annual suspended sediment concentrations, often fail to represent the dynamic nature of sediment regimes in river systems and as such, assume stationary conditions which have the potential to homogenise fluvial environments (Poole et al., 2004; Collins et al., 2011). In an attempt to improve on threshold-based targets the use of regime-based targets have been proposed (Collins et al., 2011; Collins and Pulley, 2016). Regime-based targets are founded on the principle that sediment budgets are an essential and natural geomorphic process, critical to the functioning of a diverse and healthy freshwater system, but also provide an indicator of anthropogenic impairment (Poole et al., 2004; Collins et al., 2011; Wohl et al., 2015). In addition, this approach attempts to avoid the limitations and uncertainties underpinning threshold-based targets, particularly those relating to the lack of consideration of different hydrological responses in varying river systems (Foster et al., 2011; Collins and Pulley, 2016). One example of contemporary regime-based targets was proposed by Cooper et al. (2008), this approach identified both an annual suspended sediment yield target and an annual critical suspended sediment yield target (i.e., to identify a cause for concern and a need to investigate) for five classes of river catchment topography in the UK. Alternatively, reconstructed paleolimnological data has also been used to construct historical regime-based targets for sediment in the UK (e.g., Foster et al., 2011; Rose et al., 2011).

1.6.2 The problem of accumulated fine sediment

Suspended sediment concentration targets, both threshold and regime based, are often inappropriate when considering the most ecologically detrimental aspect of the fine sediment problem in chalk streams, the accumulated fine sediment in their gravel beds (e.g., Greig et al., 2005a; Sear et al., 2016; Everall et al., 2018; Bašić et al., 2019). This has in part been attributed to the assumption of a direct and linear relationship between suspended sediment concentrations and quantities of accumulated fine sediment in riverbeds, whereby higher suspended sediment concentrations are associated with high rates of fine sediment deposition. However, this fails to consider other factors within the river system that influence the amount and rate of fine sediment accumulation such as the capacity of the system to transport fine sediment. Naden et al. (2016) demonstrated a strong correlation between the quantities of deposited fine sediment and a river system's stream power. It was highlighted that river systems with high stream powers (even with high agricultural pressure, the main source of fine sediment inputs to the systems), exhibited small amounts of deposited fine sediment, implying that these systems could transport the majority of the delivered fine sediment in suspension. In contrast, river systems with low stream powers exhibited relatively large amounts of deposited fine sediment, even with relativity low agricultural fine sediment pressure, implying that these systems were limited in their transport capacity for fine sediment. The need to consider other controlling factors in the accumulation of fine sediment, beyond suspended sediment concentrations (e.g., stream power) is particularly apparent in chalk streams given their relatively low suspended sediment concentrations compared with other river systems.

1.7 Summary

Fine sediment plays a crucial role in freshwater systems, including the transportation of nutrients and creating heterogeneous habitats. However, fine sediment inputs and loads in river systems have increased globally, attributed to the expansion and intensification of anthropogenic activities, most notably agricultural practices. As such, elevated fine sediment loads has been identified as a critical factor in the degradation of freshwater systems, in particular chalk streams. This has resulted in serious detrimental impacts for the freshwater organisms these systems support, both in terms of negative alterations to habitat suitability and direct impacts to the organisms. Despite the well-established detrimental impacts of elevated fine sediment (importantly its accumulation in gravel beds) in chalk streams and its identification as a main pollutant in the failure of chalk streams to achieve ‘good ecological status’ under the WFD, they continue to experience elevated fine sediment quantities. This in part has been attributed to the failings and assumptions underpinning current approaches to sediment targets and subsequent management in chalk streams. Most notably, the lack of consideration for the varying hydrological and sedimentological processes in different river systems and a failure to explicitly link the fine sediment pressure with its causation within a chalk stream sediment budget, the accumulation of elevated fine sediment in their gravel beds. Consequently, alternative system-based and ecologically-relevant (scientifically-based) sediment targets, that consider the causation of elevated fine sediment accumulation in chalk stream gravel beds, need to be established.

Chapter 2 Research aim, objectives, and thesis structure

2.1 Aim and objectives

Current approaches to fine sediment targets and management have failed to explicitly link the fine sediment pressure in chalk stream with its causation within the sediment budget, the accumulation of elevated fine sediment quantities within their gravel beds. This thesis aims to address this issue through the establishment of new system-specific and ecologically-relevant targets for the dominant mechanism (from the proposed chalk stream sediment budget) controlling excessive quantities of accumulated fine sediment in a typical chalk stream gravel bed. This will be addressed through the following research objectives:

1. Develop a conceptual framework for a chalk stream sediment budget, identifying the dominant mechanisms of fine sediment accumulation to prioritise revised sediment targets, management, and restoration activities.
2. Characterise the current sedimentology of UK chalk stream gravel beds (with sedimentological characteristics forming a key control on the fine sediment accumulation mechanisms).
3. Using this sedimentological information, evaluate the representation of existing models describing fine sediment–gravel bed interactions in the context of UK chalk streams (and the resultant implications for management of fine sediment accumulation mechanisms).
4. Propose new targets for the identified fine sediment accumulation mechanism (from the proposed chalk stream sediment budget), based on experiments designed to be more closely representative of UK chalk stream gravel beds.

2.2 Thesis structure

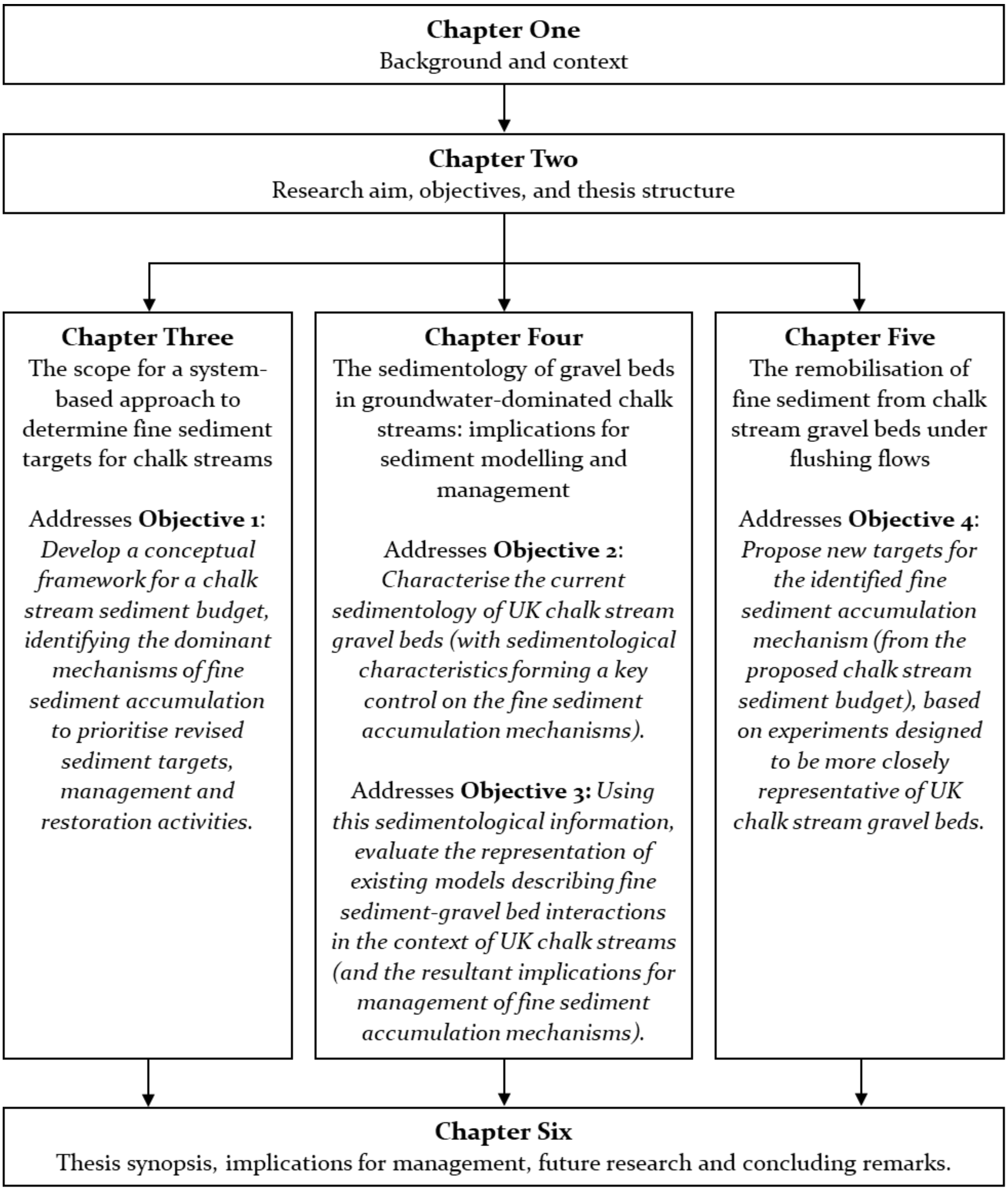
This thesis follows the “Thesis by publication format” established by the University of Southampton. The chapters were prepared as individual papers, and therefore may contain some overlapping information.

Chapter 3 addresses Objective 1, by introducing the unique geological, hydrological, and ecological responses to fine sediment within chalk streams and discusses the issues with current approaches to fine sediment targets with particular reference to chalk streams. The chapter addresses the identified issues by proposing an alternative approach to revised sediment targets and management in chalk streams; whereby a system-based sediment budget conceptual framework is developed, highlighting the overarching mechanisms controlling fine sediment accumulation in their gravel beds. The chapter concludes by identifying the dominant mechanism, with the aim to prioritise revised restoration and management activities in chalk streams. The work presented in this chapter has been published in CATENA (Mondon et al., 2021).

Chapter 4 addresses Objective 2 and Objective 3 and determines the natural sedimentological characteristics of chalk stream gravel beds, including the distribution, quantity, and composition of fine sediment, based on freeze-core data previously collated from multiple studies and reports from across the UK. The chapter then discusses to what extent the current published theoretical and experimental knowledge into the transportation and accumulation of fine sediment in gravel beds is representative of the natural conditions and processes observed in chalk stream gravel beds and the implications this will have on the modelling of fine sediment and gravel bed interactions in chalk streams. The determined typical UK chalk stream gravel bed grain size distribution (GSD) was used in the flume experiments in Chapter 5. The work presented in this chapter has been published in River Research and Applications (Mondon et al., 2024).

Chapter 5 addresses Objective 4 and establishes the near bed shear stresses and shear velocities required to remobilise fine sediment, most notably silts and clays (<62 μm), from the ecologically-sensitive surface layer (0 – 10 cm) of a typical chalk stream gravel beds through a flume study. GSDs, representative of a typical chalk stream gravel bed, of both the gravel bed and fine sediment fractions were determined through analysis in Chapter 4. The results from this flume study were then used to validate pre-established models used to predict cleanout depths of sand from an immobile gravel bed and establish whether they can efficiently predict cleanout depths of silts and clay from chalk stream gravel beds.

Chapter 6 provides a synthesis of the research presented in this thesis and discusses the practical applications of this work in relation to potential revised management and restoration activities. The limitations of the research and potential for future work are also discussed. Finally, the overall conclusions of the research are stated.



Chapter One
Background and context

Chapter Two
Research aim, objectives, and thesis structure

Chapter Three
The scope for a system-based approach to determine fine sediment targets for chalk streams

Addresses **Objective 1**: *Develop a conceptual framework for a chalk stream sediment budget, identifying the dominant mechanisms of fine sediment accumulation to prioritise revised sediment targets, management and restoration activities.*

Chapter Four
The sedimentology of gravel beds in groundwater-dominated chalk streams: implications for sediment modelling and management

Addresses **Objective 2**: *Characterise the current sedimentology of UK chalk stream gravel beds (with sedimentological characteristics forming a key control on the fine sediment accumulation mechanisms).*

Addresses **Objective 3:** *Using this sedimentological information, evaluate the representation of existing models describing fine sediment-gravel bed interactions in the context of UK chalk streams (and the resultant implications for management of fine sediment accumulation mechanisms).*

Chapter Five
The remobilisation of fine sediment from chalk stream gravel beds under flushing flows

Addresses **Objective 4**: *Propose new targets for the identified fine sediment accumulation mechanism (from the proposed chalk stream sediment budget), based on experiments designed to be more closely representative of UK chalk stream gravel beds.*

Chapter Six
Thesis synopsis, implications for management, future research and concluding remarks.

Figure 2.1: The structure of the thesis, detailing which chapters address the outlined objectives in Section 2.1.

Chapter 3 The scope for a system-based approach to determine fine sediment targets for chalk streams

This chapter has been published as:

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Author contributions:

Concept of this paper was developed by Beth Mondon and supervisors (co-authors), research of literature, development of conceptual framework, writing and editing was undertaken by Beth Mondon.

3.1 Abstract

Fine sediment has a critical role in river ecosystems and is essential for habitat heterogeneity, ecosystem structure and function. Expansion and intensification of specific land uses, including agriculture, have increased fine sediment inputs into river networks. The detrimental impacts of excessive fine sediment on river ecosystems have been well documented and numerous sediment targets have been proposed or adopted to assess the gap between target and current levels of fine sediment. Where sediment targets exist, these are often over-simplified and applied across a wide range of river environments irrespective of the processes of fine sediment deposition and the tolerance or sensitivity of river biota to fine sediment. Thus, targets often fail to provide a reliable basis for identifying the need for management interventions to restore ecosystem health. This review adopts a system-based approach to the impacts of fine sediment after reviewing the suitability of existing targets for guiding management in chalk stream catchments specifically. Chalk streams are groundwater-dominated systems characterised by stable hydrological, ecological, and thermal regimes and thus respond differently to elevated fine sediment compared with other fluvial systems. Chalk streams are often subject to high levels of sedimentation and siltation despite their low suspended sediment loads. In this paper, we review the characteristic processes and dynamics of chalk streams and how these influence fine sediment accumulation. The impacts of elevated fine sediment on chalk stream habitats and biota and the role ecosystem engineers play in the processes of

fine sediment dynamics are discussed. Finally, we discuss the application of fine sediment targets for chalk streams in relation to the implementation of both source and process-based techniques for meeting the requirement for improved ecosystem management.

3.2 Introduction

Elevated levels of fine sediment, defined as inorganic and organic particles <2 mm in diameter, have been identified as one of the principal factors leading to the degradation of freshwater ecosystems globally (Malmqvist and Rundle, 2002; Dodds et al., 2013; Zhang et al., 2014; Wilkes et al., 2019). Accelerated sediment loss is known to have pronounced negative effects on aquatic flora and fauna (Wood and Armitage, 1997; Bilotta and Brazier, 2008; Kemp et al., 2011; Jones et al., 2012a; 2017), via a number of processes including reductions in light as a consequence of elevated turbidity (Barko and Smart, 1986; Robertson et al., 2006) and the colmation of bed gravels, whereby fine sediment infiltrates and accumulates within the gravel bed framework, blocking interstitial pore spaces and reducing intra-gravel permeability and porosity (Veličković, 2005; Sear et al., 2008; Grischek and Bartak, 2016; Fetzer et al., 2017; Wharton et al., 2017).

Numerous sediment management targets and guidelines (Collins et al., 2011) have been proposed in an attempt to address the issue of elevated fine sediment. However, on a global basis, only a few such targets have been implemented as part of national legislation, since scientific debate on sediment management targets has continued without reaching consensus (Walling et al., 2007; Collins et al., 2011). These include, for example, the now repealed EU FFD annual mean suspended sediment concentration target of 25 mg L^{-1} (78/659/EC). Consequently, elevated fine sediment loads, and the resultant bed accumulation of fine sediment have remained a marked problem within rivers and for the organisms they support, particularly for lowland systems in heavily agricultural catchments (Naden et al., 2016). However, groundwater-dominated chalk streams are at an even greatest risk of elevated fine sediment inputs. Chalk streams are characterised by stable flow, thermal and nutrient regimes, and clean gravels beds. These habitats support a diverse community of nationally and internationally protected species e.g., extensive Ranunculus beds, Atlantic salmon (*S. salar* L.) and white-clawed crayfish (*A. pallipes* L.) (Mainstone, 1999). Despite naturally presenting with averagely low suspended sediment yields compared with other lowland river systems (Heywood and Walling, 2003; Walling et al., 2007; Cooper et al., 2008), chalk streams gravel beds regularly exhibit substantially higher proportions of fine sediment compared with other gravel bed systems (Acornley and Sear, 1999; Milan et al., 2000; Sear et al., 2008). This has been attributed to the combination of natural hydrological conditions, most notably low bed mobilising flows (Sear et al., 2006; 2008), and several anthropogenic activities. Shifts in land-use practices in chalk stream catchments including the expansion and intensification of autumn-sown winter cereal production and the amalgamation of small fields into larger fields, have increased erosion, runoff, and field to river connectivity (Boardman, 2003; Johannsen and Armitage, 2010; Boardman, 2013; Grabowski and Gurnell, 2016; Evans, 2017). This has increased fine sediment inputs to chalk streams, with an estimated 72-76% of fine sediment entering water courses in England and Wales originating from diffuse agricultural sources (Collins et al., 2009; Zhang et al., 2014). Furthermore, anthropogenic activities influence not only the key sources and delivery pathways of fine sediment, but also its physico-chemical characteristics (Krishnappan et al., 2020). These issues have been further compounded in chalk streams via the over-abstraction of the chalk aquifers, reducing groundwater inputs, and channel modifications (such as weirs and straightening) homogenising flow conditions, all of which encourage fine sediment deposition and further limit bed mobilising flows (Bickerton et al., 1993; Petts et al., 1999; Wohl, 2015). The inability of chalk streams to remobilise accumulated fine sediment from their gravel beds, coupled with the relative immobility of chalk stream organisms during critical life-cycle stages (e.g., some benthic invertebrates and incubating lithophilic eggs), creates high potential for long-lasting and lethal/sub-lethal impacts from accumulated fine sediment in chalk streams (e.g., Greig et al., 2005a; Sear et al., 2016; Everall et al., 2018; Bašić et al., 2019). For example, the colmation of chalk stream gravel beds, blocking intra-gravel flows and reducing dissolved oxygen concentrations, has been highlighted as a leading factor in the observed decline of spawning Atlantic salmon (*S. salar* L.) recruitment and stocks across southern chalk streams (Acornley and Sear, 1999; Greig et al., 2005a; Heywood and Walling, 2007; Cefas et al., 2018; 2019). The fine sediment problem in chalk streams is further complicated by the high presence of ecosystem engineers, e.g., the well-established role of aquatic macrophytes within the sediment budget of chalk streams (e.g., Cotton et al., 2006; Gurnell et al., 2006; Heppell et al., 2009). Attempts to re-naturalise river habitats in cases where fine sediment pressures have remained untreated risk, increased fine sediment accumulation (Sear, 1994).

This situation highlights the failings of current management targets to identify the widespread need for intervention in the first place and, in some countries, the ongoing absence of scientifically robust sediment management targets for specific river systems, including chalk streams, to avoid the previous failures associated with a single strategic target irrespective of river system type (Collins and Anthony, 2008a). This has been attributed to the inherent problems and assumptions underpinning generic regulatory standards, most of which originate from the initial failure to determine truly ecologically-relevant sediment thresholds (Collins and Anthony, 2008a). Regulatory sediment thresholds often fail to consider the complex interactions of factors involved in ecological impacts and are often biased towards more socio-economically important (e.g., salmonid) species (Collins and Anthony, 2008a; Collins et al., 2011), despite a wide range of aquatic species being impacted (e.g., Descloux et al., 2013; Berli et al., 2014; Rosewarne et al., 2014; Bašić et al., 2019). Current ecological sediment thresholds also fail to consider the implications that arise from sediment-associated organic matter, an often overlooked but critical aspect of the observed ecological impacts (Greig et al., 2007; Collins et al., 2011; Murphy et al., 2015; Naden et al., 2016). The presence of organic matter associated with infiltrating fine sediment has been highlighted as having significant influence on dissolved oxygen concentrations within bed gravels and thus impacts the spawning success of lithophilous fish (Greig et al., 2007; Sear et al., 2016) and survival of other organisms dependent upon benthic habitats for critical life stages (Von Bertrab et al., 2013; Murphy et al., 2015). Previous sediment targets have been over-simplified and yet applied strategically to a wide range of fluvial environments irrespective of (1) ecosystem functioning or differences in the organism-specific and/or (2) location-specific interactions with and responses to fine sediment inputs. Inclusion of such geographically varied factors in sediment targets, however, necessarily adds another level of complexity for the management of fine sediment. For example, the inclusion of targets for sediment-associated organic matter introduces the need to consider a far greater range of catchment sources than currently scoped within conventional sediment management strategies, including in-channel biota, riparian vegetation litter, damaged road verges and septic waste (Collins et al., 2010; 2014; 2017; Sear et al., 2017; Zhang et al., 2017a). A possible means to address the problems associated with overly-simplistic strategic sediment management targets is to determine system-based targets, centred on the understanding of the system sediment budget and ecological responses to elevated fine sediment pressure and subsequent impacts.

Given the above context, the paper reviews the hydromorphological, anthropogenic and ecological characteristics of chalk streams that set them apart from other UK fluvial systems and justifies the use of system-based targets for chalk streams. The challenges and failing of current approaches to sediment targets with specific reference to chalk streams are reviewed. We then propose an alternative system-based approach, whereby the distinctive chalk stream geomorphological, hydrological, and ecological responses to fine sediment are considered. In this context, the roles and influence of biological feedback cycles and ecosystem engineers in relation to fine sediment impacts in chalk streams are discussed.

3.3 Chalk stream river systems

Chalk streams are defined as rivers with a base-flow index (river flow derived from groundwater aquifers) exceeding 75% and a course which runs over chalk geology. Based on this definition, the UK is home to 85% of global chalk streams, located in a SW-NE chalk outcrop (O'Neill and Hughes, 2014; Figure 3.1).

3.3.1 Chalk stream hydromorphology

Chalk streams are predominantly groundwater-dominated and not strongly impacted by storm-runoff; subsequently their flow regimes have distinctly seasonal pattens and are less flashy than streams on impermeable geology. Discharges are greatest during the winter and spring months and lowest during summer and autumn months due to the seasonal recharge of the chalk aquifer (Berrie, 1992; Heywood and Walling, 2003; Grapes et al., 2005; Sear et al., 2006). However, the presence of other geologies, such as impermeable Jurassic clays within the River Nadder catchment (Heywood and Walling, 2003) or overlying glacial deposits within the River Nar catchments (Sear et al., 2006), can make these particular systems flashier and more responsive to localised events. The unmodified channel form of chalk streams reflects the stable flow regime, with high width to depth ratios, limited connectivity between land surface and river networks, and low rates of active bank erosion (Sear et al., 1999; Whiting and Moog, 2001; Heywood and Walling, 2003). Subsequently, there is an absence of sediment available for transport and thus, natural background concentrations of suspended sediment in chalk streams are substantially lower than other fluvial systems in the UK (Acornley and Sear, 1999; Walling and Amos, 1999; Heywood and Walling, 2003). Chalk streams regularly exhibit suspended sediment yields of <5 t km^{-2} year^{-1}, whereas other UK fluvial systems can have suspended sediment yields of >100 t km^{-2} year^{-1} (Heywood and Walling, 2003; Walling et al., 2007; Cooper et al., 2008). As a result, chalk streams should naturally lack elevated sediment storage (Acornley and Sear, 1999; Sear et al., 1999; 2010). Limited sediment storage can also be explained by the lack of available energy for bedload transport that is characteristic of chalk streams (Acornley and Sear, 1999; Sear et al., 1999; 2008). In addition, the armouring of gravel beds and concretion of substrates by calcareous deposits (tufa) further limit chalk stream bedload transport (Acornley and Sear, 1999; Sear et al., 1999; 2006).

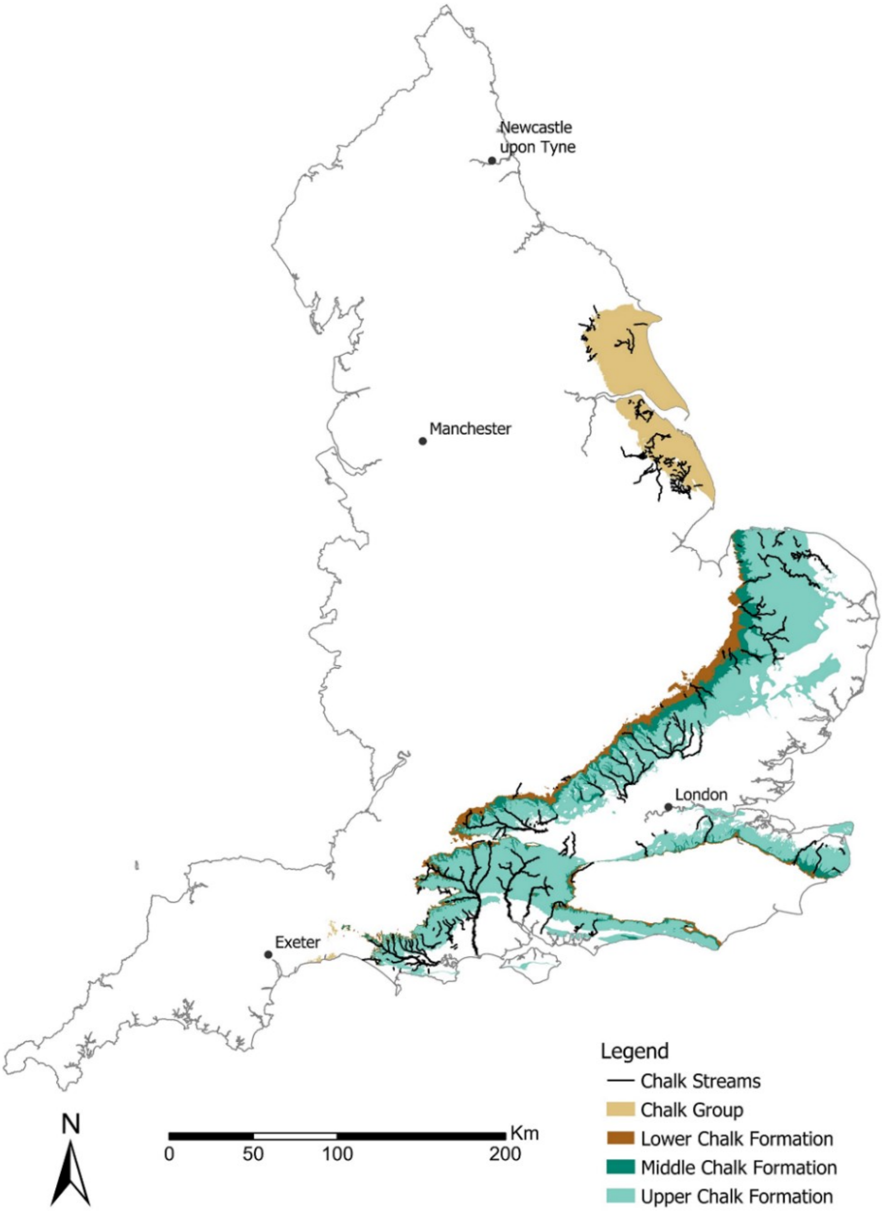
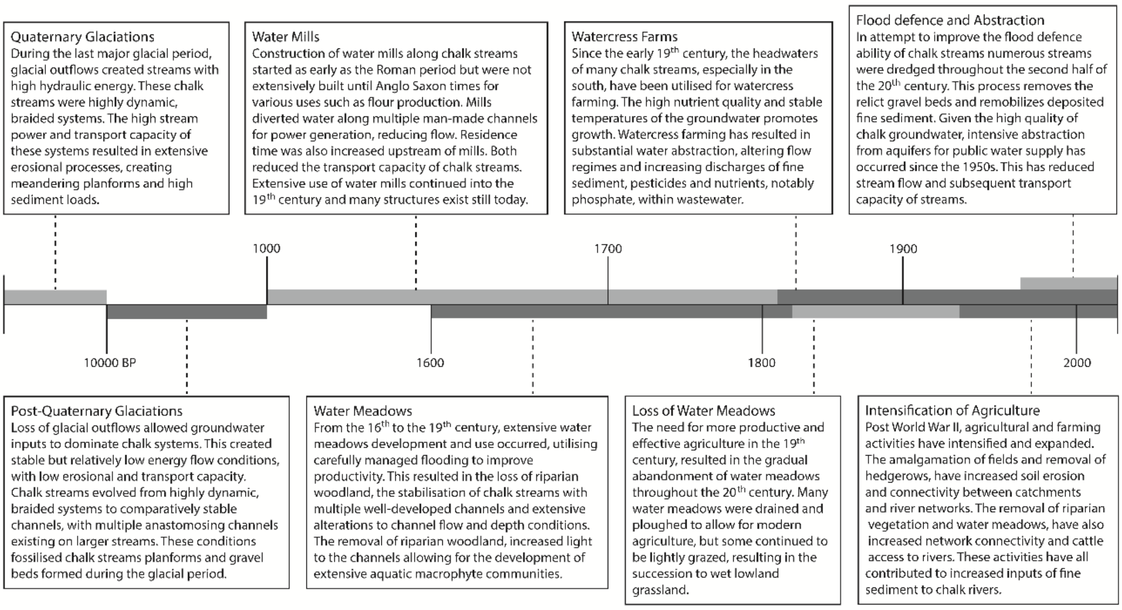


Figure 3.1: Distribution of chalk geology and the occurrence of chalk streams within the UK (Data accessed: British Geological Survey, 2008; Ordnance Survey, 2020).

3.3.2 Human activities

Chalk streams have been subjected to substantial human modifications and activities for centuries and have subsequently followed the same trajectory of change observed in most lowland river systems across Europe (Brown et al., 2018). Figure 3.2

summarises the periods of substantial human modifications and activities that have influenced the hydromorphology of contemporary chalk streams and which, cumulatively, influence their ability to process elevated sediment loads. However, the detrimental impacts associated with some anthropogenic human activities and modifications are more pronounced in chalk stream catchments, compared with other lowland systems, due to the discussed characteristic hydromorphology of chalk streams.



Quaternary Glaciations
During the last major glacial period, glacial outflows created streams with high hydraulic energy. These chalk streams were highly dynamic, braided systems. The high stream power and transport capacity of these systems resulted in extensive erosional processes, creating meandering planforms and high sediment loads.

Water Mills
Construction of water mills along chalk streams started as early as the Roman period but were not extensively built until Anglo Saxon times for various uses such as flour production. Mills diverted water along multiple man-made channels for power generation, reducing flow. Residence time was also increased upstream of mills. Both reduced the transport capacity of chalk streams. Extensive use of water mills continued into the 19th century and many structures exist still today.

Watercress Farms
Since the early 19th century, the headwaters of many chalk streams, especially in the south, have been utilised for watercress farming. The high nutrient quality and stable temperatures of the groundwater promotes growth. Watercress farming has resulted in substantial water abstraction, altering flow regimes and increasing discharges of fine sediment, pesticides and nutrients, notably phosphate, within wastewater.

Flood defence and Abstraction
In attempt to improve the flood defence ability of chalk streams numerous streams were dredged throughout the second half of the 20th century. This process removes the relict gravel beds and remobilizes deposited fine sediment. Given the high quality of chalk groundwater, intensive abstraction from aquifers for public water supply has occurred since the 1950s. This has reduced stream flow and subsequent transport capacity of streams.

Post-Quaternary Glaciations
Loss of glacial outflows allowed groundwater inputs to dominate chalk systems. This created stable but relatively low energy flow conditions, with low erosional and transport capacity. Chalk streams evolved from highly dynamic, braided systems to comparatively stable channels, with multiple anastomosing channels existing on larger streams. These conditions fossilised chalk streams planforms and gravel beds formed during the glacial period.

Water Meadows
From the 16th to the 19th century, extensive water meadows development and use occurred, utilising carefully managed flooding to improve productivity. This resulted in the loss of riparian woodland, the stabilisation of chalk streams with multiple well-developed channels and extensive alterations to channel flow and depth conditions. The removal of riparian woodland, increased light to the channels allowing for the development of extensive aquatic macrophyte communities.

Loss of Water Meadows
The need for more productive and effective agriculture in the 19th century, resulted in the gradual abandonment of water meadows throughout the 20th century. Many water meadows were drained and ploughed to allow for modern agriculture, but some continued to be lightly grazed, resulting in the succession to wet lowland grassland.

Intensification of Agriculture
Post World War II, agricultural and farming activities have intensified and expanded. The amalgamation of fields and removal of hedgerows, have increased soil erosion and connectivity between catchments and river networks. The removal of riparian vegetation and water meadows, have also increased network connectivity and cattle access to rivers. These activities have all contributed to increased inputs of fine sediment to chalk rivers.

Figure 3.2: A generic chalk stream timeline, detailing substantial periods of human modifications that have resulted in changes in chalk stream systems and their catchments (Westlake et al., 1972; Berrie, 1992; Casey and Smith, 1994; Mainstone, 1999; Sear et al., 1999; Walling and Amos, 1999; Neal et al., 2000; Ladle and Westlake, 2006; Grabowski and Gurnell, 2016; Historic England, 2017; Brown et al., 2018).

The shift in agricultural land-use since the 20th century and subsequent increase in mobilisation and delivery of fine sediment to river networks is not unique to chalk stream catchments. However, the change in chalk stream catchments from predominantly pasture and low intensity farmland, to cultivated and high intensity autumn-sown cereal production has increased bare, tilled soils that are highly susceptible to erosion (Boardman, 2003; Collins and Walling, 2007a; Johannsen and Armitage, 2010; Grabowski and Gurnell, 2016; Evans, 2017). In addition, some chalk stream catchments coincide with the occurrence of loessic deposits (Antoine et al., 2003). Soils derived from loess have a propensity to crust during heavy rainfall events, decreasing rates of infiltration and increasing rates of runoff and erosion (Boardman, 2003; 2020). The risk of erosion and runoff has been further compounded by the amalgamation of smaller fields into larger fields and removal of hedgerows, increasing delivery pathways and field-channel connectivity (Boardman, 2013; Grabowski and Gurnell, 2016; Evans, 2017; Boardman et al., 2019). Furthermore, the increased use of heavier farming equipment and shifts from predominantly sheep to cattle farming in chalk catchments have increased runoff and fine sediment erosion through widespread soil compaction decreasing infiltration rates (Bilotta et al., 2007; Evans, 2017). Including, in wheelings established during in-field operations for cereal cropping which is considered a significant contributing factor in soil erosion and runoff in chalk catchments (Withers et al., 2007; Boardman et al., 2019; Boardman, 2020). The role of increased connectivity between river networks and agricultural land has become more apparent in recent years (Fuller and Death, 2018; Boardman et al., 2019); the associated impacts are potentially even greater in chalk streams given their natural lack of connectivity between the land surface and river networks. The combination of these changes in agricultural activities has made chalk catchments more prone to erosion and runoff compared with other lowland agricultural areas (Boardman, 2003; 2013; Evans, 2017) and has been a significant driver in the elevated inputs of fine sediment into chalk streams. Damaged road verges, the destabilisation of banks due to cattle access, watercress farming and sewage treatment plant effluent further compound the diffuse pollution problems associated with fine sediment storage in chalk catchments (Casey and Smith, 1994; Neal et al., 2000; Collins et al., 2010; Bond, 2012).

The impacts of elevated inputs of fine sediment have been compounded by alterations and modifications to chalk stream channel conditions and flow regimes. Over-abstraction from chalk aquifers for farming and potable supplies reduces groundwater inputs and has been widely cited as the cause of reduced flows observed in chalk streams, especially during drought years (Bickerton et al., 1993; Wood and Petts, 1999; House and Punchard, 2007), further limiting the characteristically low bed-mobilising flows, promoting fine sediment deposition. Extensive water meadows were established across southern chalk catchments during the 17th and 18th century (Historic England, 2017) and some eastern catchments, particularly the River Nar and Stiffkey (Martins and Williamson, 1994; Sear et al., 2006). Managed modern-day water meadows have been demonstrated to act as sediment sinks (Cook et al., 2017). However, most water meadows have been left to degrade or ploughed leaving behind relict features and artificial channels. Such relict features, including weirs, water mills and straightened artificial channels have altered the hydromorphological conditions within chalk streams (Mainstone, 1999; Lenders et al., 2016; Historic England, 2017), homogenising flow conditions and increasing residence times, promoting sediment accumulation. In addition, these activities often resulted in the removal of riparian vegetation; this increased insolation to channels, contributing to the development of the now protected characteristic instream macrophyte communities. Concomitantly, this also removed riparian buffering, further increasing land surface to river network connectivity, and increasing inputs of fine sediment.

3.3.3 Ecology of chalk streams

The characteristics of chalk streams provide unique habitats for a wide range of freshwater organisms. The biological communities often reflect the longitudinal change in hydrological conditions within chalk streams; for example, the naturally intermittent headwaters "*winterbournes*" species exhibit traits which make them resilient to intermittent flows including drought-resistant eggs and high dispersal potential (Wright et al., 1984; Armitage and Bass, 2013), including both aquatic and terrestrial specialist species of conservation interest (Bunting et al., 2021). The characteristic gravel beds provide ideal habitat for a rich benthic macroinvertebrate community and spawning conditions for lithophilous fish species. The stable flow, temperature and nutrient regimes, and clear water create conditions for extensive instream macrophyte communities (Westlake et al., 1972; Berrie, 1992). A number of chalk stream species are protected under national and international (European) laws and are notifiable features in the designation of many UK chalk stream Sites of Special Scientific Interest (SSSI) and Special Areas of Conservation (SAC) (Table 3.1).

Table 3.1: Characteristic chalk stream aquatic organisms that have been designated as priority species and the chalk stream fluvial habitat they are most commonly found in (SAC – Special Area of Conservation, BAP – Biodiversity Action Plan Priority Species). Adapted from Mainstone (1999).

Ecological group	*Species*	*Winterbourne*	*Perennial*	*Designation*
Aquatic macrophytes	Pond water-crowfoot (*Ranunculus peltatus)*	✓	✓	SAC – Annex I habitat.
	Stream water-crowfoot (*Ranunculus penicillatus subsp. pseudofluitans)*		✓	SAC – Annex I habitat.
	River water-crowfoot (*Ranunculus fluitans*)		✓	SAC – Annex I habitat.
Macro-invertebrates	Southern damselfly (*Coenagrion mercuriale*)		✓	SAC – Annex II species, BAP.
	White-clawed crayfish (*Austropotamobius pallipes*)		✓	SAC – Annex II species, BAP.
	Desmoulin's whorl snail (*Vertigo moulinsiana*)	✓	✓	SAC – Annex II species, BAP.
Fish	Atlantic salmon (*Salmo salar*)	✓[a, b]	✓	SAC – Annex II species, BAP.
	Brown trout (*Salmo trutta*)	✓[a, b]	✓	BAP.
	Brook lamprey (*Lampetra planeri*)	✓[b]	✓	SAC – Annex II species.
	River lamprey (*Lampetra fluviatilis*)	✓[b]	✓	SAC – Annex II species, BAP.
	Sea lamprey (*Petromyzon marinus*)		✓	SAC – Annex II species, BAP.
	Bullhead (*Cottus gobio*)	✓[b]	✓	SAC – Annex II species.
	Spined loach (*Cobitis taenia*)	✓[b]	✓	SAC – Annex II species, BAP.

a – Only during spawning season

b – Only when sufficient flow conditions persist.

3.3.3.1 Ecosystem engineers

Many of the organisms found in chalk streams modify their physical habitat, affecting ecosystem processes and community structure, and are thus referred to as ecosystem 'engineers' (Jones et al., 1994) and subsequently, can have substantial effects on the chalk stream sediment budget. Most notably in chalk streams, this is represented by the role of extensive instream and marginal vegetation (Gurnell et al., 2006; Heppell et al., 2009). Seasonal vegetation growth creates a diverse mosaic of hydraulic conditions which promote fine sediment deposition within macrophyte patches due to reduced velocity and create localised areas of increased velocity between patches which scour fine sediment from the gravel bed (Gurnell et al., 2006; Wharton et al., 2006), the degree of which is altered by species and spatial distribution (Gurnell et al., 2006; Heppell et al., 2009; Licci et al., 2019). In addition, abundant instream macrophytes maintain higher velocities despite lower summer groundwater discharges (Wharton et al., 2006). The presence of woody debris instream can also influence the spatial variability of sediment dynamics, resulting in both flushing of fine sediments and rapid accumulation in ponded areas (Sear et al., 2010; Osei et al., 2015; Parker et al., 2017).

Chalk stream species are also known to increase gravel bed mobility and locally increase bedload transport of fine sediment via the disturbance of bed material, which increases particle protrusion, decreasing the force required for mobilisation. Here, examples include the spawning activities of lithophilous fish such as Atlantic salmon (*S. salar* L.*)* (DeVries, 2012), the foraging activities of benthic fish such as bullhead (*Cottus gobio* L.*)* (Rice et al., 2019), and macroinvertebrates such as invasive signal crayfish (*P. leniusculus* D.) (Johnson et al., 2010; Mathers et al., 2019). Conversely, refugia building activities by fish and macroinvertebrates can stabilise gravel beds by physically adding resisting forces (e.g., sticky nets) and reducing near bed shear stress through the removal of finer particles from the surface layers of the bed (Statzner et al., 1999; Johnson et al., 2009). Chalk stream species can contribute to increased loads of fine sediment, e.g., egestion of faecal pellets by black-fly larvae (*Diptera: Simuliidae*) (Wotton et al., 1998; Wharton et al., 2006) and river bank borrowing by invasive signal crayfish (*P. leniusculus* D.) (Faller et al., 2016). Diatom and biofilm communities can also influence bed stabilisation within the surface layers of the riverbed through the production of EPS, which bind fine sediment together and enhance sediment stability by increasing the critical shear stress required for particle entrainment (Fang et al., 2014; Gerbersdorf and Wieprecht, 2015). However, the extent of influence by diatom and biofilm communities on the chalk stream sediment budget is yet to be established.

3.3.3.2 Ecological impacts of elevated fine sediment

High concentrations of suspended sediment in the water column and elevated rates of fine sediment infiltration and accumulation within gravel beds can have substantial detrimental impacts on freshwater organisms (Table 3.2). However, the specific impacts of both suspended sediment and accumulated fine sediment within gravel beds with respect to chalk streams species, apart from incubating salmonid eggs, remain relativity under-represented in published literature. The coarse bed particles are a key habitat for characteristic chalk stream aquatic species; subsequently, elevated rates of fine sediment infiltration and accumulation within gravel beds can have substantial detrimental ecological impacts. The colmation of gravel beds can negativity influence intra-gravel permeability and porosity, thus reducing rates of dissolved oxygen exchange and the removal of metabolic waste (Sear et al., 2014; 2016; Wharton et al., 2017). The detrimental impacts associated with this on the survival and recruitment of incubating salmonid eggs and emerging alevins (e.g., Atlantic salmon (*S. salar* L.) and Brown trout (*S. trutta* L.)), has been well established (Greig et al., 2005a; 2005b; 2007; Sear and DeVries, 2008; Pattison et al., 2014; Sear et al., 2016; 2017). However, there has been limited focus on the implications of chalk stream gravel bed colmation for the progeny of non-salmonid fish, despite the fact that 85% of lithophilic fishes in Europe are non-salmonids (Bašić et al., 2019) and multiple other chalk stream species require similar spawning habitats (e.g., Bullheads, *C. gobio* L.; Tomlinson and Perrow, 2003). The few examples include, reduced incubating egg survival for Dace (*Leuciscus leuciscus* L.) (Mills, 1981) and premature emergence for European barbel (*B. barbus* L.), with negative implications for post-emergent larval survival (Bašić et al., 2019).

The colmation of gravel beds homogenises the benthic habitat and reduces available pore space. This, in combination with reduced intra-gravel flows and dissolved oxygen concentrations, has been noted to have negative implications for chalk stream macroinvertebrate communities, including, decreases in species diversity and shifts in community assemblages, favouring species with small body sizes, short lifecycles, or high mobility (e.g., Descloux et al., 2013; Murphy et al., 2015). However, only a few studies have investigated the exact implications of elevated fine sediment loads and accumulation on individual chalk stream macroinvertebrate species. Examples include elevated suspended sediment loads increasing abrasion and irritation of white-clawed crayfish (*A. pallipes* L.) gills, decreases in feeding and respiration ability (Rosewarne et al., 2014), and elevated fine sediment deposition in gravel beds increasing incubating mayfly (*S. ignita* P.) egg mortality, via suffocation and dislodgement (Everall et al., 2018). Colmation can also alter the stable water temperatures characteristic of chalk streams, due to reduced hyporheic exchange limiting groundwater upwelling (Brunke, 1999; Wharton et al., 2017). This can have critical implications for chalk stream species; for example, Brown trout (*S. trutta* L.)

eggs were observed to hatch and emerge earlier than predicted due to the warming of riverbed gravels (Acornley, 1999). It should be noted however, that some key chalk streams species are more resilient to elevated loads of fine sediment or even require it during critical lifecycle stages such as European river lamprey (*L. fluviatilis* L.) ammocoete recruitment (Silva et al., 2015). Overall, the specific impacts of both elevated suspended sediment and accumulated fine sediment within the gravel beds of chalk streams remain relativity under-represented in published literature and what does exist has mostly been focused on the implications for incubating salmonid eggs. Nevertheless, what information does exist demonstrates that chalk stream species are generally negatively influenced by elevated rates of fine sediment accumulation within gravel beds.

Table 3.2: Summary of the general impacts of elevated loads of suspended sediment and elevated accumulation of fines in the stream bed on aquatic organism ecological groups.

Ecological group	*Elevated suspended sediment in the water column*	*Increased deposition and infiltration of fine sediment into gravel beds*	*Reference*
Biofilms & Diatoms	Scouring and dislodgment due to abrasion. Decreased photosynthetic activity and growth. Shifts in community assemblages towards single celled and motile species.	Smothering of benthic periphyton. Shifts in community assemblages towards single celled and motile species. Decreased species diversity.	Dickman et al. (2005); Francoeur and Biggs (2006); Izagirre et al. (2009); Neif et al. (2017).
Aquatic macrophytes	Decreased photosynthetic activity and growth. Damage to macrophyte stands and leaves through abrasion.	Burial of individual stands. Reductions in growth, due to alterations in available nutrients and dissolved oxygen concentration to root systems.	Barko and Smart (1986); Bilotta and Brazier (2008); Jones et al. (2012b).
Macro-invertebrates	Abrasion and irritation of exposed structures such as gills and feeding apparatus. Decreased feeding and respiration ability. Scouring and dislodgment due to abrasion. Increased drift.	Suffocation and burial of individuals. Reduced dissolved oxygen to benthic species. Shifts in community assemblages towards certain functional groups. Decreased species diversity. Increased egg mortality.	Rabení et al. (2005); Bo et al. (2007); Rosewarne et al. (2014); Béjar et al. (2017); Everall et al. (2018); Mathers et al. (2018).
Fish	Increased avoidance behaviours. Decreased swimming performance. Abrasion and irritation of gill lamellae. Respiratory impairment. Reduced growth rates. Reduced feeding/foraging rates. Decreased predator-prey interactions and success.	Reducing dissolved oxygen supply to eggs. Blocking of egg membrane micropores. Reduced spawning success. Increased egg mortality via suffocation. Reduced alevin emergence. Altered timing in alevin emergence and post-emergence survival.	Greig et al. (2005a; 2005b); Sutherland and Meyer (2007); Shoup and Wahl (2009); Berli et al. (2014); Sear et al. (2016); Bašić et al. (2019).

3.3.4 Sediment associated organic matter

Despite being identified as a potentially lethal and/or sublethal aspect of fine sediment within aquatic ecosystems for a number of decades, the detrimental ecological impacts associated with organic matter within deposited fine sediment have yet to be considered in sediment targets. The infiltration of organic matter not only affects the interconnectivity of the gravel framework via the physical blocking of interstitial pore spaces, but also decreases intra-gravel dissolved oxygen concentrations through increased biological oxygen demand (BOD) during decomposition (Greig et al., 2007; Sear and DeVries, 2008; Sear et al., 2016). In addition, the presence of organic matter can facilitate the growth of biofilms, further limiting intra-gravel flows and thus reducing dissolved oxygen availability (Greig et al., 2005a; 2007; Sear et al., 2016). However, apart from a few studies investigating the impacts of different sediment sources on incubating salmonid egg survival and macroinvertebrates (e.g., Louhi et al., 2011; Murphy et al., 2015; Sear et al., 2016), studies of the implications of organic matter content for chalk stream organisms appear somewhat rarely in published literature. Therefore, the extent to which organic matter affects the majority of chalk stream organisms can only be assumed. The impacts of organic matter content of infiltrating fine sediment could be extensive within a chalk stream as these systems regularly exhibit high proportions of organic matter within accumulated fine sediment compared with other UK fluvial systems (Sear et al., 1999; Greig et al., 2005a; Heywood and Walling, 2007). The presence of abundant aquatic macrophytes throughout chalk streams contributes in this respect (Bateman, 2012; Collins et al., 2017; Zhang et al., 2017a). Anthropogenic activities also contribute to the relativity high organic matter content. For example, reaches directly downstream of watercress farms have recorded high proportions of organic matter derived directly from the watercress farms (Casey and Smith, 1994).

3.3.5 Summary

The inability of chalk streams to remobilise fine sediment from their gravel beds, due to their natural hydrological conditions e.g., stable groundwater-dominated and low bed mobilising flows, has resulted in the propensity for chalk stream gravel beds to accumulate high quantities of fine sediment compared with other fluvial systems. Anthropogenic activities such as over-abstraction of groundwater and elevated fine sediment inputs resulting from changes in chalk stream catchment land use have compounded the effects of characteristic low bed mobilising flows. This coupled with the immobility of chalk stream gravel bed organisms during critical life cycle stages (e.g., benthic invertebrates and incubating lithophilic eggs) (Clarke and Wharton, 2001; UK Biodiversity Action Plan Steering Group for Chalk Rivers, 2004), has resulted in significant ecological degradation in chalk streams. Subsequently, this has precipitated investment in costly mitigation actions, including for example, the Catchment Sensitive Farming initiative (Collins et al., 2007), gravel washing (Bašić et al., 2017) and modifications to channel morphology designed to flush fine sediments from surface gravels (Pander et al., 2015). Despite this, currently only 16.7% of chalk streams are classified as being in "good ecological status" or higher under the EU Water Framework Directive (Environment Agency, 2020), with fine sediment highlighted as a key factor contributing to the degradation of chalk streams and the habitats they provide (Collins and Walling, 2007b; Grabowski and Gurnell, 2016). This highlights the need for improved fine sediment targets that consider the distinct hydromorphological, ecological, and anthropogenic characteristics of chalk streams that set them aside from other lowland fluvial systems both in the UK and internationally.

3.4 Current approaches to sediment targets

A number of sediment targets have been proposed to assist with the management of excessive fine sediment, but only a few have been effectively implemented as part of governmental legislation (Walling et al., 2007). Approaches to setting sediment targets are currently split into two distinct categories (Collins et al., 2011); water column (Table 3.3) or river substrate metrics (Table 3.4). Water column metrics include turbidity, suspended sediment concentration summary statistics and sediment regimes. River substrate metrics consider substrate composition/embeddedness, intra-gravel dissolved oxygen concentration and riffle stability.

Currently, the USA is the only country to have introduced a statutory programme of setting targets for sediment loads in freshwater ecosystems. Section 303(d) of the Clean Water Act (1972) requires States to determine and document impaired water systems and establish total maximum daily loads (TMDLs) (Borah et al., 2006). In contrast, the main legislation for the management of freshwater ecosystems within the European Union (EU), the WFD, fails to outline any critical standard for fine sediment, despite identifying suspended material (critically, both the inorganic and organic fractions) as a main pollutant (Cooper et al., 2008; Grove et al., 2015). Consequently, the majority of EU member states, including the UK, still loosely rely on the annual mean suspended sediment target of 25 mg L^{-1} in the repealed EU FFD, although this is not enforced by any statutory bodies. In the UK, additional suspended sediment targets have been applied to wastewater discharges from various sources such as watercress and fish farms, but apart from the target directed at water treatment work discharges (Table 3.3), these were all repealed in 2018 and have yet to be replaced (Environment Agency, 2018a; 2018b). There also exists a number of biomonitoring indices within the UK, where the extent of fine sediment stress can be inferred from the assemblage of benthic macroinvertebrates found instream using biotic indices (e.g., Murphy et al., 2015; Turley et al., 2016; Extence et al., 2017; Murphy et al., 2017). Although biomonitoring indices offer a potential way towards setting sediment targets, they lack the explicit link to the causation of elevated fine sediment loads and accumulation and thus, suitable mitigation strategies.

Table 3.3: Examples of current fine sediment targets and water quality guidelines for water column metrics (NTU – nephelometric turbidity units).

Country/State	*Criteria*	*Standard*	*Reference*
UK (Water treatment works)	Suspended Solids	Default permit standard of 100 mg L^{-1} in wastewater discharges.	Environment Agency (2018a)
USA (Alaska)	Turbidity	Not to exceed 5 NTU above <50 NTU or 10% increase above >50 NTU.	ANZECC (2000)
USA (California)	Turbidity	Not to exceed 1 NTU above 0 – 5 NTU or 20% increase 5 – 50 NTU.	California Department of Fish and Game (2003)
USA (Idaho)	Turbidity	Not to exceed 50 NTU instantaneous or 25 NTU for <10 days or exceed 10 NTU in summer flows.	ANZECC (2000)
USA (Montana)	Turbidity	No increase in background turbidity except under short-term authorisation.	Rowe et al. (2003)
USA (Oregon)	Turbidity	<10% increase relative to control point.	Rowe et al. (2003)
USA (Nevada)	Turbidity	10 NTU in cold water reaches. 50 NTU in warm water reaches.	Rowe et al. (2003)
USA (Utah & Wyoming)	Turbidity	Not to exceed 10 NTU above background levels.	Rowe et al. (2003)
Canada (British Columbia)	Turbidity	Not to exceed 5 NTU above <50 NTU or 10% increase above >50 NTU.	Rowe et al. (2003)
	Total suspended solids	Not to exceed 10 mg L^{-1} above >100 mg L^{-1} or 10% increase above <100 mg L^{-1}.	Rowe et al. (2003)
Canada (General)	Turbidity	Clear flow: Max increase of 8 NTU over background (<24 hrs). High flow: Not exceed 10% increase (background >8 NTU).	CCME (2002); CCME (2003)
New Zealand	Turbidity	4.1 NTU (upland), 5.6 NTU (lowland).	ANZECC (2000)
Australia (SE)	Turbidity	2 – 25 NTU (upland), 60 – 50 NTU (lowland).	ANZECC (2000)
Australia (SW)	Turbidity	10 – 20 NTU (upland and lowland).	ANZECC (2000)
Australia (Tropical)	Turbidity	2 – 15 NTU (upland and lowland).	ANZECC (2000)
Australia (S. central)	Turbidity	1 – 50 NTU (upland and lowland).	ANZECC (2000)

Table 3.4: Examples of current fine sediment targets and water quality guidelines for bed substrate metrics.

Country/State	*Criteria*	*Standard*	*Reference*
USA (Alaska)	% fine sediment (by mass)	Not to exceed 5% increase or 30% of weight (0.1 – 4 mm).	ANZECC (2000)
USA (Arizona)	% fine sediment in riffles	Not to exceed 35% of weight.	Benoy et al. (2012)
USA (California)	% embeddedness in riffles	≤25% or decreasing trend towards.	California Department of Fish and Game (2003); Benoy et al. (2012)
	% fine sediment in redds (by mass)	≤14% < 0.85 mm. ≤20% < 6.4 mm.	
USA (Hawaii)	Fine sediment deposition (thickness over stream bottom)	Not to exceed 5 mm in hard bottom streams. Not to exceed 10 mm in soft bottom streams.	Benoy et al. (2012)
USA (Idaho)	% fine sediment in riffles (by mass)	Not exceed 10% of subsurface sediment (<0.85 mm).	ANZECC (2000)
USA (Montana)	% fine sediment in riffles (by mass)	Not to exceed 30% of sediment (<63 mm).	Rowe et al. (2003)
	Intra-gravel dissolved oxygen	1-day minimum of 5.0 mg L^{-1}. 7-day mean ≥6.5 mg L^{-1}.	Rowe et al. (2003)
USA (Oregon)	% fine sediment in riffles (by mass)	Long term trend towards <20% (<2 mm).	Benoy et al. (2012)
Canada (British Colombia)	% fine sediment (by mass) in redds	Not to exceed 10% (2 mm), 19% (<3 mm) or 25% (<6.35 mm).	Rowe et al. (2003)

3.4.1 Unsuitability of current approaches to sediment targets for chalk streams

Appropriate sediment targets must be established for chalk streams to quantify the need for intervention and the magnitude of change to be expected of any management strategy. However, simply transferring existing approaches to setting sediment targets and guidelines from other countries is not appropriate, due to significant differences in climatic, hydrological, and anthropogenic conditions (Walling et al., 2007), particularly with respect to the unique hydromorphological conditions within chalk streams, i.e., stable flow regimes, low suspended sediment yields and limited bed mobilising flows. Collins et al. (2011) noted that current approaches to determining sediment targets are underpinned by a number of inherent problems and assumptions that result in oversimplification of freshwater systems and bias in establishing the negative effects of fine sediment on freshwater organisms, making them unsuitable for chalk streams.

Most notably, the current use of a single, blanket annual mean suspended sediment target across multiple systems in Europe is, arguably, inappropriate, given the high spatial and temporal variability and diversity of sediment budgets within fluvial systems (Collins and Anthony, 2008b; Collins et al., 2011). This is particularly apparent in chalk streams, which regularly have suspended sediment yields substantially lower than other fluvial systems within the UK (Walling et al., 2007; Cooper et al., 2008; Bilotta et al., 2012). However, even the use of system-specific annual suspended sediment targets is not sufficient to provide a basis for effective and successful management in chalk streams, given temporal variations in sediment budgets which vary as a result of changes in seasonal discharges, local morphology, and storm conditions (Collins and Anthony, 2008b; Cooper et al., 2008). Despite this, sediment export in chalk streams does not often occur in a pattern that could be considered a robust baseline against which guidelines could be set and, therefore, is not considered a suitable approach. In addition, the use of single suspended sediment concentration targets assumes that there is a simple, direct linear concentration-ecological response to fine sediment, whereby increasing concentrations results in increasing ecological degradation. Adverse effects can manifest at lower concentrations due to complications arising from the interplay of additional factors influencing the effects of fine sediment, including timing of delivery, grain size and quality, exposure duration, proportion of inorganic and organic material, sediment source and species life-cycle stage (e.g., Greig et al., 2007; Sear et al., 2016; Bašić et al., 2019). For example, Mayfly eggs (*S. ignita* P.) experienced 45% mortality when exposed to 20 mg L^{-1} of fine sediment for 72 days, but after 183 days of exposure mortality increased to 80% (Everall et al., 2018). Uncertainties regarding sediment impacts have also resulted from a large amount of variability and uncertainty in published data detailing the impacts of elevated fine sediment concentrations in chalk streams, arising from a variety of techniques used in the measurement of fine sediment pressure, responses of aquatic organisms, and the units used (Table 3.5). The lack of standardisation prevents meaningful comparison of studies and establishment of effective and meaningful targets based on current evidence. Therefore, a degree of standardisation of data is required, especially when developing ecologically-based targets for chalk streams with respect to species across multiple trophic levels. Furthermore, there has been a bias towards more socio-economically valuable species within the published data detailing the impacts of fine sediment within chalk streams, for which much published data focuses on the impacts on incubating salmonid eggs (e.g., Acornley and Sear, 1999; Greig et al., 2005a; Pattison et al., 2014; Sear et al., 2016).

Even if the interplay of additional factors were to be considered more explicitly, the use of suspended sediment targets alone does not address the main cause of ecological degradation in chalk streams, i.e., the deposition and accumulation of fine sediment within the gravel bed framework. Currently, only the USA and Canada have distinct targets for both water column metrics and bed substrate metrics (Table 3.3 and Table 3.4). The failure to consider this could have arisen from the assumption that the degree of colmation within the gravel bed framework is directly proportional to the suspended sediment load. However, this assumption fails to consider the other factors that influence chalk stream gravel bed colmation, such as low bed mobilising flows, the ratio between infiltrating fines and the gravel framework, particle properties, organic matter content, hyporheic exchange and the role of ecosystem engineers. Subsequently, current approaches to fine sediment targets have failed to explicitly link ecological degradation in chalk streams with causation and thus, successful mitigation. A new approach to system-based fine sediment targets for chalk streams, therefore, should be determined that focuses on the colmation of the gravel beds, encompasses water column and bed substrate metrics, and which considers the numerous mechanisms controlling them.

Table 3.5: Examples of the range in critical thresholds for the effects of fine sediment on chalk stream biota (SS – suspended sediment, N/A – not available, NTU – nephelometric turbidity units).

Biota	*Life stage*	*SS concentration/ accumulation*	*Exposure (hrs)*	*Sediment type*	*Organic content (%)*	*Effects*	*Reference*
Ephemeroptera (Baetis rhodani) and Isopoda (Asellus aquaticus)	*N/A*	5 mm	*N/A*	125 μm > 4 mm	*N/A*	Burial	Wood et al. (2005)
		250 -2000 mg L^{-1}	*N/A*	<63 μm	*N/A*	Increased drift.	
Invertebrates e.g., Ephemeroptera (Baetis rhodani)	*N/A*	4 – 5 kgm^{-2}	*N/A*	Sand	*N/A*	Increased drift. Reduced density.	Larsen and Ormerod (2010)
Mayfly (Serratella ignita)	Egg	10 – 20 mg L^{-1}	1704	5 – 100 μm	*N/A*	10 – 45% mortality.	Everall et al. (2018)
	Egg	10 – 20 mg L^{-1}	4392	5 – 100 μm	*N/A*	20 – 80% mortality.	
White-clawed crayfish (Austropotamobius pallipes)	Juvenile	42 mg L^{-1}	1080	*N/A*	*N/A*	Sediment accumulation in 92% of individuals. 25% gill area affected.	Rosewarne et al. (2014)
	Juvenile	65-133 mg L^{-1}	1080	*N/A*	*N/A*	Sediment accumulation in 100% of individuals. 40 – 60% gill area affected.	
Atlantic salmon (Salmo salar)	Adult	20 mg L^{-1}	*N/A*	*N/A*	*N/A*	Increased foraging.	Robertson et al. (2006)
	Adult	60 – 180 mg L^{-1}	*N/A*	*N/A*	*N/A*	Avoidance behaviour.	
	Egg	9 – 14% of redd	1776	<2 mm	13	50 – 100% mortality.	Heywood and Walling (2007)
	Egg	8 – 12% of redd	1776	<1 mm	*N/A*	50 – 100% mortality.	
	Egg	10% of red mass	*N/A*	<2 mm	19.7	91.3% mean mortality.	Greig et al. (2005a)
Brown trout (Salmo trutta)	Juvenile	13 – 62 NTU	*N/A*	*N/A*	*N/A*	13 – 38% reduction in swimming performance.	Berli et al. (2014)

3.5 Gravel bed sediment budgets as an overarching framework for informing bed management targets for chalk stream systems

Current approaches to fine sediment targets have failed to explicitly link the colmation of chalk stream gravel beds and its causation. Subsequently, we propose a sediment budget-based approach, whereby all the mechanisms controlling gravel bed framework colmation in chalk streams are considered explicitly. Since the gravel bed sediment (organic and inorganic) budget is a component of the overall catchment sediment budget, catchment sources must also be considered as part of a conceptual framework for informing successful and robust fine sediment targets and effective management. Whilst controlling fine sediment mass *per se*, regardless of source, is important with regard to lethal impacts, consideration of the specific sources of sediment can be important for more subtle sub-lethal impacts (Collins et al., 2011; Sear et al., 2016).

3.5.1 Chalk stream gravel bed sediment budget framework

We propose that the gravel bed sediment budget be separated into the overarching mechanisms controlling the accumulation of fine sediment in chalk streams. The colmation of chalk stream gravel beds is controlled by numerous interacting physical, chemical, and biological factors both from the catchment and instream. These factors can be split into four distinct overarching mechanisms (Figure 3.3, Figure 3.4, Figure 3.5): (A) inputs of fine sediment into a channel system from the surrounding catchment and/or channel margins; (B) transport of fine sediment in the water column as suspended load or bedload; (C) infiltration of fine sediment into gravel beds, and; (D) exfiltration of fine sediment from gravel beds. The interplay of these four mechanisms in the channel bed sediment budget, determines the amount of fine sediment accumulation and thereby the propensity for detrimental impacts on the sensitive aquatic biota hosted by chalk streams.

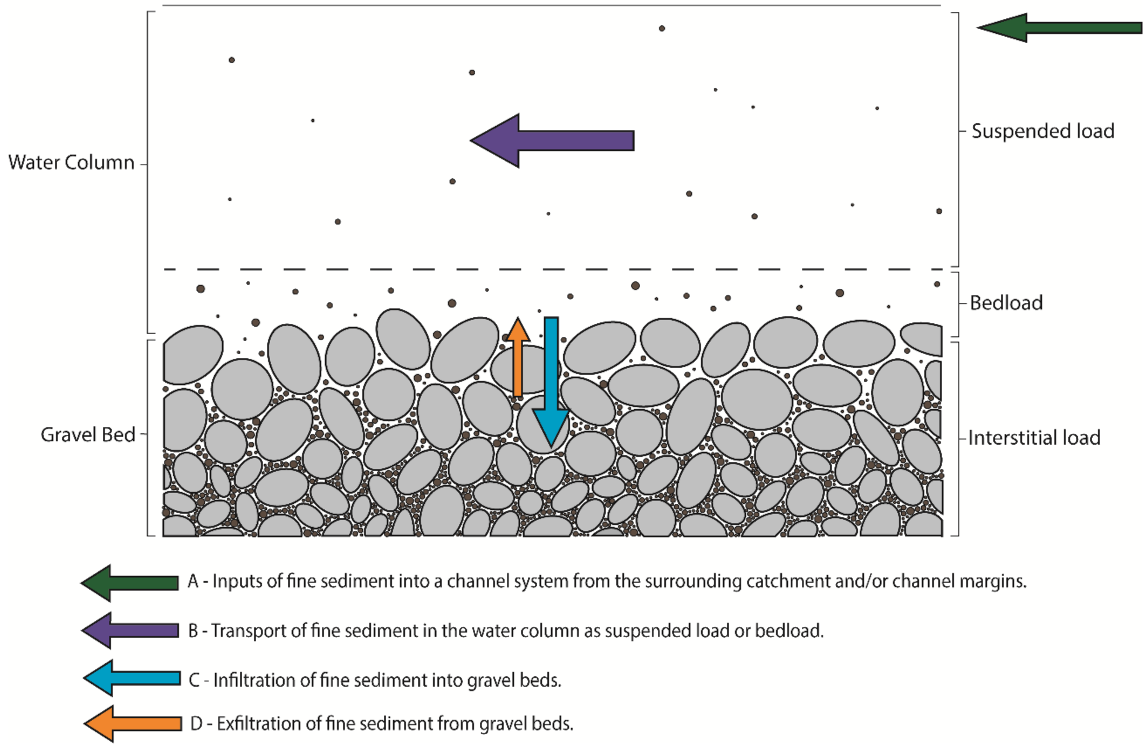


Figure 3.3: Schematic of a chalk stream gravel bed, showing the four interacting mechanisms that control the degree of gravel bed colmation: **A**. inputs of fine sediment into the channel system from the surrounding catchment and/or channel margins; **B**. transport of fine sediment in the water column as suspended load or bedload; **C**. infiltration of fine sediment into the gravel beds; **D**. exfiltration of fine sediment from the gravel beds.

3.5.1.1 Mechanism A – Inputs of fine sediment into the channel system from the surrounding catchment and/or instream sources

Inputs of fine sediment into river networks are primarily determined by the availability of sediment in the catchment, the mobilisation and/or transport capacity of the erosive agent (e.g., precipitation, overland flow) and the efficiency of connectivity pathways between potential sources and the stream network (Perks et al., 2015; Vercruysse et al., 2017). Alterations to these factors modify the amount of fine sediment delivery to a channel system. In chalk stream catchments, agricultural activities dominate catchment-based fine sediment sources; most notably, intensive autumn-sown winter cereal production has increased the presence of bare tilled soils prone to elevated rates of erosion and runoff. Fine sediment can originate from other sources in chalk catchments such as eroding riverbanks, construction sites and damaged road verges (Fryirs, 2013; Collins et al., 2014). In chalk streams, inputs from river-bank erosion are relatively low compared with other lowland river systems due to the stable flow regime; however, this has increased due to cattle trampling destabilising the banks, contributing to the elevated sediment loads (Bond, 2012). Cattle access to streams is retained so that farmers avoid the cost of alternative water supplies. There are also numerous sources of sediment-associated organic matter within chalk stream catchments; for example, damaged road verges have been noted to be substantial contributors to inputs, with a recorded 11-48% of sediment-associated organic matter originating from this source (Collins et al., 2014; 2017). These inputs, both organic and inorganic, have been further compounded by the presence of large fields, a lack of hedgerows and limited riparian vegetation, increasing delivery pathways and field-to-river connectivity (Boardman, 2013; Grabowski and Gurnell, 2016; Boardman et al., 2019). The impacts associated with catchment connectivity are potentially even greater in chalk streams due to the naturally limited catchment-to-river connectivity.

Instream sources of fine sediment also exist within chalk streams. For example, the precipitation of calcium carbonate in upwelling groundwater in chalk streams results in the production of low-density tufa deposits, which can contribute substantially to the bed material load (Acornley and Sear, 1999; Sear et al., 1999). In addition, there can be biological sources of fine sediment in chalk streams such as faecal pellets from blackfly larvae (*Diptera: Simuliidae*) (Wotton et al., 1998). Natural erosion of channel bank sources is typically low relative to other river types where rates are higher and banks represent a major sediment source, although the biological processes of ecosystem engineers can influence this: e.g., invasive signal crayfish (*P. leniusculus* D.) burrowing has increased this source of fine sediment since their introduction into UK rivers in the mid-1970s (Harvey et al., 2014; Faller et al., 2016). Decaying instream vegetation also can represent a source of sediment-associated organic matter within chalk streams, contributing significantly to instream sources during seasonal macrophyte die-back (Bateman, 2012; Jones et al., 2012b; Collins et al., 2017).

In addition to spatial differences in inputs of fine sediment to chalk streams there are also temporal differences. The cultivation of autumn-sown cereals involves large areas of bare or poorly vegetated ground from October to December; this coincides with the period of the year when rainfall intensity is greatest, further accelerating sediment loss (Grabowski and Gurnell, 2016; Boardman, 2020). Subsequently, inputs of agriculture fine sediment are likely to be greater during winter months in chalk streams. Furthermore, this occurrence of higher agricultural fine sediment inputs coincides with the spawning periods of major fish families in chalk streams, such as salmonidae, cottidae, and petromyzontidae (Kemp et al., 2011). Decaying instream vegetation also can represent an important temporal source of sediment-associated organic matter within chalk streams, contributing significantly to instream sources during seasonal macrophyte die-back (Bateman, 2012; Jones et al., 2012b; Collins et al., 2017). Similarly, management of weed creates an additional opportunity for sediment release including production of organic matter at the time of cutting.

3.5.1.2 Mechanism B – Transport of fine sediment in the water column as suspended load or bedload

The load of fine sediment within a system is determined by the relationship between rates of inputs, flow conditions (such as turbulence), and the characteristics of the suspended particles, such as density and size (Brunke, 1999; Wilkes et al., 2019). The sediment mode of transport moving through the water column can include bedload, suspended load or a combination of both, depending on the relationship between sediment size and the transport capacity of the system (Owens et al., 2005; Sear et al., 2008; Hemond and Fechner, 2015). Bedload transport consists of particles that when mobilised remain in near continual contact with the gravel bed and generally consists of coarser sediments e.g., coarser sands (Hemond and Fechner, 2015). The suspended sediment load is the fraction of the total particulate load transported by flow turbulence within the water column and consists of finer particles e.g., silts, clays, and organic matter (Owens et al., 2005; Walling and Collins, 2016). Sand particles can be transported as either bedload or suspended load depending on the hydraulic conditions within the system (Curran and Wilcock, 2005). In chalk streams, there is little or no mobility of the framework gravels, given the relatively low bed shear stress (Sear et al., 2008; 2009). Therefore, the bed material load that occurs in chalk streams is dominated by sands and tufa fragments, and the majority of the sediment load is carried in suspension (Sear et al., 1999). In these conditions, chalk stream gravel beds often develop a static armour layer on the surface of the bed, whereby the larger grains are over-represented on the surface compared with their population in the substratum (Wilcock and DeTemple, 2005; Curran and Tan, 2014). The characteristic low bed mobilising flows of chalk streams generate shear stresses less than those needed to entrain the coarser gravels but sufficient to mobilise the finer particles and, over time, fines are selectivity removed from the surface layer (Curran and Waters, 2014; Curran and Tan, 2014). The presence of coarser sediments in the armour layer of chalk stream gravel beds can further influence the transport of fine sediment; for example, the bed roughness generated by the presence of coarse particles increases flow turbulence and thus increases the concentration of particles in suspension (Recking et al., 2008; Perret et al., 2019).

Once fine sediments are in suspension, the distance they travel downstream and the rate of deposition is dependent on the flow turbulence conditions, the subsequent transport capacity within the chalk stream and the characteristics of the suspended particles (Brunke, 1999; Bui et al., 2019; Wilkes et al., 2019). Spatial changes in flow can alter the transport capacity of a chalk stream; for example, channel modifications such as weirs and mill structures, can reduce the flow velocity upstream of structures through increased residence times, increasing the rate of sediment deposition. The influence of these modifications on the sediment budget of chalk streams is demonstrated in Figure 3.4. In addition, the straightening and over-widening of chalk stream channels can homogenise flow conditions and create extensive marginal dead-water zones, increasing sediment deposition in concert with the growth of marginal vegetation (Sear et al., 2000). Temporal variations in flow can also alter the ability of chalk stream systems to transport sediment; most notable here, are the seasonal variations in groundwater inputs altering discharges. It can therefore be assumed that the ability of chalk streams to mobilise and transport sediment is reduced in summer and autumn months due to the reduced discharges from groundwater inputs. Over-abstraction of the chalk aquifers can compound the reduced flows in summers months, further limiting transport capacity, and increasing the potential for sediment deposition (Bickerton et al., 1993; Petts et al., 1999; Collins et al., 2005). Conversely, the extensive beds of aquatic macrophytes (emergent and submerged) in chalk streams, during summer months, can maintain higher velocities despite lower discharges (Wharton et al., 2006).

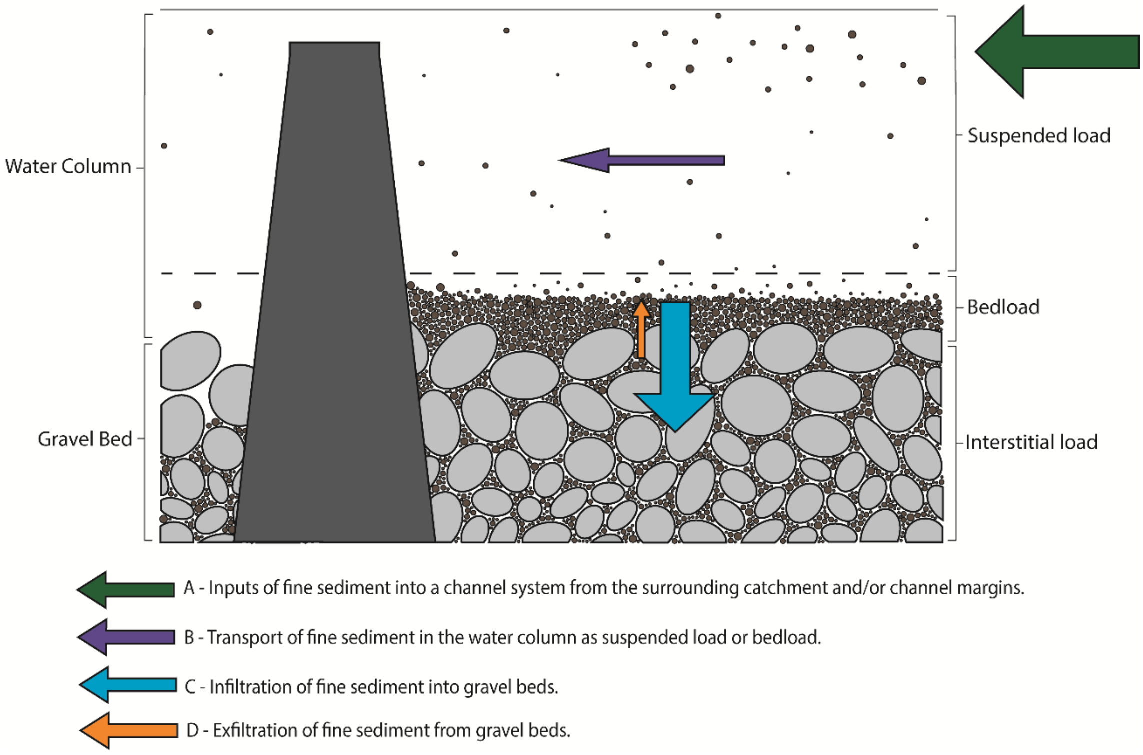


Figure 3.4: Schematic of a chalk stream gravel bed, showing how the four interacting mechanisms that control the degree of gravel bed colmation are influenced by increased fine sediment input, from the intensification of agriculture and reduced flow velocity due to channel modifications such as weirs: **A**. inputs of fine sediment into the channel system and/or the channel margins; **B**. transport of fine sediment in the water column as suspended load or bedload; **C**. infiltration of fine sediment into the gravel bed; **D**. exfiltration of fine sediment from the gravel bed.

3.5.1.3 Mechanism C – Infiltration of fine sediment into the riverbed gravels

The infiltration (colmation) of fine sediment into the riverbed of chalk streams, includes the intrusion of fine sediment into the coarse gravel framework, its infiltration to the hyporheic zone and the formation of a layer that reduces permeability of the gravel bed (Brunke and Gonser, 1997; Brunke, 1999; Veličković, 2005; Wharton et al., 2017). The infiltration of fines is dependent on the flow velocity, shear stresses, and suspended sediment concentrations of the chalk stream. Other influential factors include, the hydraulic gradient of the seepage flow, grain size distribution and particle shape of the infiltrating fine sediment and gravel bed substrate, quantity of sediment-associated organic material and the presence of ecosystem engineers such as aquatic macrophytes, invertebrates, fish, and biofilms (Brunke, 1999; Veličković, 2005; Rice et al., 2016; Wharton et al., 2017). The comparative grain size distributions of the infiltrating fine sediment and the gravel bed framework has been demonstrated to be a controlling factor in the initial fine sediment intrusion, whereas intra-gravel pore sizes are critical in the determination of infiltration depth (Cui et al., 2008; Wooster et al., 2008). If the interstitial spaces are sufficiently large, unimpeded static percolation (USP) occurs, whereby the infilling fine sediment infiltrates to an impermeable layer and subsequently infills pores over the whole overlying depth (Herrero and Berni, 2016; Dudill et al., 2017). However, if the interstitial spaces are smaller than the infilling sediments, bridging occurs, where the deposited sediment is trapped at the pore throats, creating a clogged layer at the surface (Gibson et al., 2009; Herrero and Berni, 2016). However, within chalk stream gravel beds, it is not currently known which infiltration mechanism is dominant.

As with Mechanism B, the low bed mobilising flows characteristic of chalk streams is a major controlling factor in the degree of fine sediment infiltration. Subsequently, it can be assumed that rates of Mechanism C in chalk streams are relativity high during both summer months, when reduced groundwater inputs further limit the bed mobilising flow, and during winter, when suspended sediment loads are high due to elevated agricultural inputs. There are also biological and chemical processes that can increase Mechanism C in chalk streams (Figure 3.3), including increased roughness induced by aquatic macrophytes, large wood jams, and variability in fine sediment transport capacity resulting from channel widening or reduced hydraulic gradient; e.g., upstream of hatches or weirs (Cotton et al., 2006; Heppell et al., 2009; Sear et al., 2009). In addition, biological processes can reduce fine sediment infiltration. For example, the occurrence of biofilms and EPS within the gravel framework can reduce the quantity and infiltration depth of deposited fine sediment via the blocking of intra-gravel pores (Salant, 2011).

3.5.1.4 Mechanism D – Exfiltration of fine sediment from the riverbed gravels

The final mechanism that controls the colmation of gravel bed frameworks in chalk streams is the exfiltration of fine sediment, which can re-establish the permeability of the streambed, as fine sediment is remobilised from the gravel bed framework (Wharton et al., 2017). The factors controlling this mechanism are strongly interrelated and, in some cases, also control infiltration. Within chalk streams the dominant factors are bed mobilising flows, intra-gravel flows and arrangement of bed sediments (Petticrew et al., 2007; Casas-Mulet et al., 2017). Therefore, spatial variations in the streambed morphology, hydraulic conditions and the presence of ecosystem engineers can create areas with varying levels of susceptibility to fine sediment exfiltration (Wharton et al., 2017). The stability of bed sediments is determined by the balance between mobilising and resisting forces, typically defined by mean or turbulent shear stress (Voepel et al., 2019). These are counteracted by the forces within the particles that resist erosion such as gravity, friction, cohesion, and adhesion (Grabowski et al., 2012; Voepel et al., 2019). The erosion threshold is the force required to initiate mobility and entrainment of fine sediment, which occurs when the shear-force exerted on particles by flowing water exceeds the erosion threshold (Turowski et al., 2011; Grabowski et al., 2012; Voepel et al., 2019). The erosion threshold is influenced by various properties of the fine sediment and the gravel bed, including grain size distribution, arrangement in the bed, bulk density, organic matter content and biological processes e.g., the production of EPS and occurrence of aquatic macrophytes (Hanson and Simon, 2001; Grabowski et al., 2012; Hodge et al., 2013). Subsequently, fine sediment exfiltration from the surface layers of the chalk stream gravel bed can be achieved through increased flow velocities and shear stress; however, bedload movements are required to allow the flushing of fine sediment from the lower substratum, without which permanent colmation will occur. This is further complicated in the gravel beds of chalk streams due to the presence of surface armour layers, which shelter fine substratum particles from remobilisation (Parker and Sutherland, 1990; Wharton et al., 2017), limiting the exfiltration of fine sediment from the subsurface layers. However, the low bed mobilising flows characteristic of chalk streams, mean that the exfiltration of fine sediment is minimal or even non-existent without other influencing factors which would increase flow heterogeneity such as the presence of instream vegetation or large wood. As a consequence, chalk streams are more prone to fine sediment accumulation because, unlike other river types whose hydrological regime or slope generate bed mobilising events, their infiltration load is greater than their exfiltration load (Sear et al., 2008).

Erosion thresholds and subsequently, rates of Mechanism D have been demonstrated to have significant temporal variations in chalk streams, peaking in autumn, mostly corresponding to the seasonal changes in baseflows and ecosystem engineer abundance (Grabowski et al., 2012). Exfiltration rates in chalk streams can be further complicated by the presence of cations, particularly calcium, concentrations of which are highest when the baseflow is compromised, predominantly by groundwater inputs (autumn months). Dissolved cations increase the cohesion of clay particles and can stabilise EPS frameworks present in gravel beds (Grabowski et al., 2012). The same human activities and modifications that have altered the infiltration of fine sediment also alter the exfiltration of fine sediment from chalk stream gravel beds. Reductions in flow turbulence and bed mobilising flows due to over-abstraction and channel modifications have further limited fine sediment exfiltration from gravel bed frameworks and have therefore promoted colmation in chalk streams. Despite this, there has been increasing evidence in recent years for the importance of biological processes in the exfiltration of fine sediment from riverbeds such as bioturbation by fish, and macroinvertebrates, acting as pre-conditioning agents for exfiltration by increasing the exposure of sediment to surface shear stress (Pledger et al., 2016; Rice et al., 2016; Pledger et al., 2017; Wharton et al., 2017). These processes are expected to be of even greater importance within chalk streams, given the prevalence of ecosystem engineers, and thus need to be included within the sediment budget of chalk streams.

3.5.2 The role of ecosystem engineering controls for chalk stream gravel bed sediment budget

The role of biological communities in the sediment budgets of rivers has yet to be incorporated in the definitions of sediment targets, including those for chalk streams. However, a growing body of scientific literature highlights their importance for all four mechanisms (Figure 3.5) of the chalk stream sediment budget (Rice et al., 2016; Wilkes et al., 2019). Ecosystem engineers can influence the sediment transport systems of rivers in four ways:

1) Modifying the supply of sediment to gravel beds, Mechanisms A and C (e.g., signal crayfish burrowing in riverbanks).
2) Modifying the erodibility of sediment deposited on gravel beds, Mechanisms B and C (e.g., redd cutting by salmonids).
3) Modifying the rate of sediment accumulation and residence time on, or in gravel beds, Mechanisms B, C and D (e.g., influence of aquatic macrophytes on fine sediment deposition).
4) Modifying the transportability of fine sediments within gravel beds, Mechanism D (e.g., EPS growth occluding pores, sticking finer particles together).

Groups of aquatic organisms can have substantial effects on sediment processes within chalk streams and, consequently, influence the four mechanisms that determine the gravel bed sediment budget of chalk streams (Table 3.6; Figure 3.5).

Table 3.6: Examples of the influence of ecosystem engineers found in chalk streams on the four critical mechanisms (A, B, C and D; Figure 3.3) that control the gravel bed sediment budget and the accumulation of fine sediment in the gravel framework.

Biota	*Biological/physical activity*	*Effect*	*Influence on gravel bed sediment budget*	*Reference*
Diatom community	Creation of extracellular polymeric substances (EPS).	500% increase in critical shear stress for fine sediment (<2 mm).	Reduces Mechanism D.	Gerbersdorf et al. (2008)
Biofilm community	Creation of EPS and filamentous elements.	70% increase in incipient velocity of sediment (after 4 weeks).	Reduces Mechanism D.	Fang et al. (2014)
Aquatic macrophytes: Water crowfoot (Ranunculus spp) and watercress (Rorippa nasturtium aquaticum)	Lower turbulence and decreased transport capacity within vegetated stands.	25.5 – 66.8 kg m^{-2} deposition and storage of fine sediment (dependant on site).	Reduces Mechanism B & D. Increased Mechanism C.	Heppell et al. (2009)
	Increased turbulence and increased sediment scour around vegetated stands.		Increases Mechanism B & D. Reduces Mechanism C.	
Macroinvertebrate: Blackfly larvae (Diptera: Simuliidae)	Digestion of fine sediment and egestion of larger faecal pellets.	Increase proportion of faecal pellets in the water column downstream from blackfly aggradation.	Increased Mechanism A.	Wotton et al. (1998)
Macroinvertebrate: Net-spinning caddisfly larvae (Hydropsyche spp)	Spinning with silk: multiple activities.	Increase in critical shear stress for fine gravels, 35% (4 – 6 mm) and 23% (6 – 8 mm).	Reduces Mechanism D.	Statzner et al. (1999)
Macroinvertebrate: Case-building caddisfly larvae (e.g., Glossosmatidae and Hydropsyche)	Pupal-case building.	Community use of 15 – 20% of sediment (2.5 – 4 mm).	Reduces Mechanism C.	Statzner et al. (2005)
		Community use of averagely 37.57 gm^{-2} of sediment (0.063 – 11 mm, dependent on taxa).	Reduces Mechanism C. Increases Mechanism D.	Mason et al. (2019)

Table 3.6 continued:

Macroinvertebrate: Stonefly (Dinocras cephalotes)	Prey storage (walking while hunting).	Erosion of 75% of fine sediment (0.2 – 1 mm) from gravels (200 – 400 kg $m^{-2} yr^{-1}$).	Increases Mechanism D.	Statzner et al. (1996)
Macroinvertebrate: *Signal crayfish (Pacifasticus leniusculus)*	Bioturbation	32% (474 kg) increase to monthly base flow suspended sediment.	Increases Mechanism A & D.	Rice et al. (2016)
	Burrow creation in riverbanks.	Increased average sediment yield by 3t km^{-1} in burrowed reach.	Increases Mechanism A.	Faller et al. (2016)
Non-salmonid: *Gudgeon (Gobio gobio)*	Benthic feeding and swimming.	0.1 kg $m^{-2} d^{-1}$ increase in baseflow transport of gravel (7 – 11 mm).	Increases Mechanism D.	Statzner et al. (2003)
		2.6 kg $m^{-2} d^{-1}$ increase in baseflow transport of sand (0.4 – 0.8 mm).	Increases Mechanism D.	Statzner et al. (2003)
Non-salmonid: *Sea lamprey (Petromyzon marinus)*	Nest construction during spawning activities.	50-143% reduction in fine sediment cover and 30 – 62% reduction in embeddedness in nests.	Increases Mechanism D.	Hogg et al. (2014)
Salmonid: *Atlantic Salmon (Salmo salar)*	Redd construction during spawning activities.	Erosion of approx. 40% of fine sediment (>1 mm) from streambed gravels in redds.	Increases Mechanism D.	Kondolf et al. (1993)

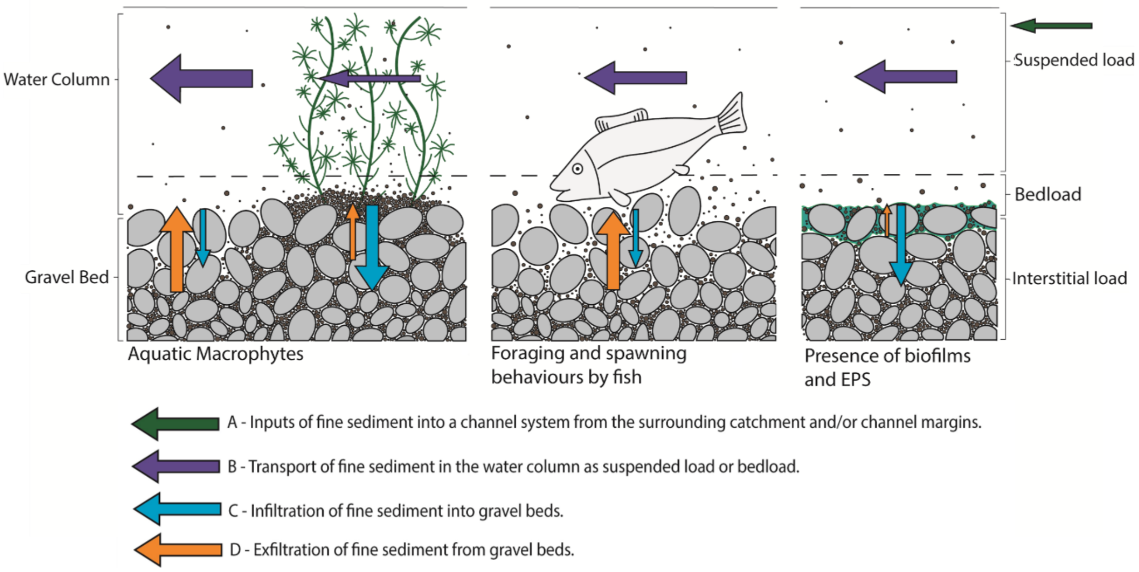


Figure 3.5: Schematic of a chalk stream gravel bed, showing how the four interacting mechanisms that control the degree of gravel bed colmation are influenced by a range of ecosystem engineers and their biological processes: **A**. inputs of fine sediment into the channel system from the surrounding catchment and/or channel margins; **B**. transport of fine sediment in the water column as suspended load or bedload; **C**. infiltration of fine sediment into the gravel bed; **D**. exfiltration of fine sediment from the gravel bed.

Only a few ecosystem engineers within chalk streams introduce new inputs of fine sediment and thereby influence Mechanism A. For example, burrow creation within the riverbanks by signal crayfish (*P. leniusculus* D.) introduces approx. 3t km^{-1} of sediment from the banks into the channel system; a sediment source that is otherwise relativity unimportant within chalk streams (Table 3.6; Faller et al., 2016). The presence of aquatic macrophytes can also introduce a new source of fine sediment into the water column due to decomposition, increasing Mechanism A. Marginal vegetation can also influence Mechanism A; acting as natural sediment transport barrier, reducing delivery pathway connectivity and stabilising banks, thereby reducing fine sediment inputs (Grabowski and Gurnell, 2016). The most notable ecosystem engineer within chalk streams that influences Mechanism B, is the seasonal growth of aquatic macrophytes, the presence of which can substantially alter flow patterns and thus the transportation of suspended sediment (Cotton et al., 2006; Gurnell et al., 2006; Heppell et al., 2009). Reductions in water velocities and shear stress (Mechanism B) within aquatic macrophytes increases fine sediment deposition and infiltration (Mechanism C) and decreases fine sediment exfiltration and remobilisation (Mechanism D). This also creates localised areas of increased velocity around macrophyte patches, increasing Mechanism B, which subsequently decreases Mechanism C and increases Mechanism D. For example, autumnal peaks in chalk stream gravel bed erosion thresholds have been demonstrated to coincide with peak coverage of aquatic macrophytes (Heppell et al., 2009; Grabowski et al., 2012). Multiple ecosystem engineers can influence the stability of the gravel bed framework and fine sediment, thus affecting the rates of Mechanism C and D. For example, the feeding and burrowing activities of benthic invertebrates such as mayfly larvae (e.g., *Ephemera danica)* and signal crayfish *(P. leniusculus* D.*)* destabilise surface sediment and expose sub-surface fine sediment to bed mobilising flows (Johnson et al., 2010; Harvey et al., 2014; Jacobus et al., 2019). Similarly, the feeding and spawning activities of lithophilous fish can increase particle protrusion and reduce friction angles, thus reducing the force required to mobilise bed particles and increasing fine sediment exfiltration (Kondolf et al., 1993; Rice et al., 2016). These activities all increase fine sediment exfiltration (Mechanism D) from the gravel bed. Conversely, the production of EPS and biofilms within, and on the surface layer of chalk stream gravel beds can decrease fine sediment exfiltration (Mechanism D) by binding the particles together. This has the potential to have significant implications for temporal variations in sediment erosion thresholds (Mechanism D) within chalk streams, especially during early spring when benthic diatoms are abundant (Grabowski et al., 2012).

3.6 Prospects

In chalk streams, low bed mobilising flows have resulted in the propensity for high quantities of fine sediment accumulation in their gravel beds. Future approaches to fine sediment targets and management need to reflect the processes that cause this, hence the proposition of a sediment budget approach for chalk streams that considers the controlling mechanisms for gravel bed colmation. However, for sediment targets to be truly ecologically-based, the bias in chalk stream ecological studies must be first addressed. In addition, the ecological impacts of the interplay of additional factors beyond fine sediment concentration must be further investigated, especially in relation to organic matter content given its typically higher prevalence in chalk streams. We therefore advocate the determination of critical ecological fine sediment accumulation thresholds for keystone species in each trophic level of chalk streams, to address the issue of species bias within current sediment targets and ecological studies within these river systems. Future sediment targets for chalk streams need to have an absolute ecological maximum value for fine sediment accumulation, which cannot be exceeded, based on the critical thresholds of keystone species in each trophic level of these river systems.

Underneath this, there would then be a range of targets based on different factors within chalk stream river networks and catchments that have been discussed above and which alter the four controlling mechanisms outlined in the proposed sediment budget framework. For example, if a system is known to experience lower flows due to over-abstraction, bed mobilising flows would be reduced, increasing rates of infiltration, and decreasing rates of exfiltration. Therefore, steps would have to be taken to reduce inputs of fine sediment (Mechanism A), such as changes to agricultural practices or mitigation options such as improved riparian buffers to ensure the absolute ecological maximum of fine sediment accumulation in gravel beds is not exceeded. Equally, steps could be taken to increase flow heterogeneity within the chalk stream channel through, for example, aquatic macrophyte management or the installation of large wood jams to encourage rates of fine sediment remobilisation and exfiltration (Mechanism D). In addition, future sediment targets for chalk streams need to consider temporal and spatial differences in the hydrological and ecological regimes within chalk streams and their catchments. For example, chalk stream sediment targets need to be more stringent during the spawning season (November-March) of key fish species (e.g., salmonidae, cottidae, and petromyzontidae). Furthermore, this period coincides with the window when chalk stream catchments are at greatest risk of erosion due to extensive bare and tilled soils; a consequence of predominately autumn-sown winter cereal production. Consequently, the ecological impacts arising from fine sediment are expected to be greater.

3.7 Conclusions

Current approaches to sediment targets have failed to provide a robust baseline to direct effective management and restoration for chalk streams, given that these ecosystems continue to be detrimentally impacted by elevated loads of fine sediment. The accumulation of fine sediment within the gravel beds of chalk streams has pronounced detrimental impacts on their ecology. This is a consequence of the inability of chalk streams to remobilise deposited fine sediment due to low bed mobilising flows and the high sediment sensitivity of chalk stream biota. Due to the detrimental impacts of accumulated fine sediment within gravel beds, it is important that future sediment targets take into consideration the multiple factors controlling the rates of fine sediment accumulation including the transport capacity of the receiving waters. Herein, we advocate a sediment budgeting approach that recognises the role of four critical processes by which fine sediment accumulates within gravel beds. Current management targets are focused on measures of only one of these processes, the suspended sediment load in the water column. In chalk streams and, indeed, other low stream power systems with gravel beds, it is the rates at which fine sediment in suspension and in the bedload, deposit and accumulate in the bed framework that controls fine sediment pressure. The absence of bed mobilising flows and high sediment-associated organic matter loads combined, result in relativity high fine sediment accumulation despite low catchment suspended sediment yields. In addition, the role of ecosystem engineers within the sediment budget needs to be considered in the determination of future sediment targets and management techniques, especially within chalk streams, due to the high prevalence and influence of ecosystem engineers on both the inputs of fine sediment and storage within the gravel beds. It should be noted that fine sediment targets are not intended to replace restoration or management techniques that would re-establish geomorphological processes within fluvial systems and catchments, but, instead, to provide a baseline against which the effectiveness of such techniques can be applied or assessed.

Chapter 4 The sedimentology of gravel beds in groundwater-dominated chalk streams: implications for sediment modelling and management

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4.1 Abstract

Elevated fine sediment accumulation in chalk stream gravel beds has long been known to cause detrimental ecological impacts. Current sediment targets and approaches to mitigation have failed due to oversimplification of hydrological responses to fine sediment and lack of relevant scientific knowledge underpinning them. A necessary first step is to better characterise the sedimentology of chalk stream gravel beds; thus, the novelty of this study was to determine the sedimentological characteristics of chalk stream gravel beds, specifically the quantity and distribution of fine sediment with depth. We collated published and unpublished freeze-core data, encompassing 90 sites across 11 UK chalk streams. Comparison was made using existing sediment metrics that link the processes of bed structuring, fine sediment infiltration and channel bed saturation. Results showed average quantities of fine sediment (<2 mm) in chalk stream gravel beds was 25% by weight, with >75% of beds exceeding thresholds for ecological degradation. Quantities of fine sediment increased with increasing depth into the bed, with an average increase between surface and subsurface layers of 54% and 89% of the gravel bed over-saturated with fine sediment. Regional differences were attributed to differences in stream power and local sediment sources, including surficial geology and catchment land use. In

addition, a major contrast was identified between experimental conditions in flume studies of fine sediment infiltration into immobile gravel beds and the natural conditions observed in chalk streams. As such, the use of such models as a basis to explore sediment management scenarios is unlikely to correctly predict the outcome of such management techniques in a real-world situation.

4.2 Introduction

Fine sediment (inorganic and organic particles <2 mm in diameter) plays a fundamentally important role in the hydrogeomorphic cycle of freshwater systems, in their habitat heterogeneity and for the delivery of nutrients, dissolved organic matter and contaminants such as microplastics and heavy metals (Owens et al., 2005; Westrich and Förstner, 2007; Chon et al., 2012; He et al., 2021). Despite this, elevated quantities of fine sediment both in the water column and, within riverbeds, can alter the natural functioning of freshwater systems, resulting in marked detrimental impacts on aquatic organisms (e.g., Robertson et al., 2006; Bo et al., 2007; Rosewarne et al., 2014; Sear et al., 2016; Bašić et al., 2019). The naturally clear water and gravel beds of chalk streams, combined with their characteristic stable flow, nutrient and temperature regimes, create ideal conditions for a wide range of nationally and internationally protected habitats and species (Berrie, 1992; Mainstone, 1999; Table 3.1). For instance, the clean coarse gravels, naturally low prevalence of fine sediment and well oxygenated intra-gravel flows, provide ideal spawning conditions for lithophilic fish such as Atlantic salmon (*S. salar* L.), Brown trout (*S. trutta* L.), and Bullhead (*C. gobio* L.) (Tomlinson and Perrow, 2003; Greig et al., 2007; Louhi et al., 2008).

However, chalk streams regularly exhibit higher quantities of fine sediment within their gravel beds compared with other gravel bed systems (Acornley and Sear, 1999; Milan et al., 2000; Sear et al., 2008; Dunscombe et al., 2018). Elevated fine sediment quantities in chalk stream gravel beds are a consequence of their natural conditions, most notably the inability to remobilise coarse framework gravels due to low stream power and the resulting stability of the gravel beds (Acornley and Sear, 1999; Sear et al., 1999; 2005). This subsequently, increases the propensity for long-lasting and lethal/sub-lethal impacts on chalk stream ecology (e.g., Greig et al., 2005a; Heywood and Walling, 2007; Rosewarne et al., 2014; Everall et al., 2018). This reflects elevated fine sediment inputs caused by the intensification of agriculture and farming practices within chalk stream catchments (Walling and Amos, 1999; Collins and Zhang, 2016; Grabowski and Gurnell, 2016). In this regard, the shift to autumn-sown winter cereal production and amalgamation of smaller fields into larger fields, have increased runoff pathway length and velocity, erosion, and connectivity between catchments and river networks (Johannsen and Armitage, 2010; Boardman, 2013; Grabowski and Gurnell, 2016; Evans, 2017; Boardman et al., 2019). In addition, centuries of instream activities such as construction of weirs and over-abstraction of chalk aquifers have reduced flows and flow velocities, further limiting bed mobility and contributing to fine sediment accumulation (Bickerton et al., 1993; Petts et al., 1999; Wood and Armitage, 1999; Wohl, 2015).

Sediment targets have been proposed to guide management of the fine sediment problem and can currently be split into two distinct categories: firstly, water column metrics, such as turbidity and suspended sediment concentrations and secondly, river substrate metrics, such as substrate composition/embeddedness, riffle stability and intra-gravel dissolved oxygen concentration (Collins et al., 2011). Targets based on suspended sediment concentrations (i.e., the repealed European Union (EU) FFD annual mean target of 25 mg L^{-1} (78/659/EC)), are not scientifically robust and are undermined by a number of inherent problems and assumptions, particularly in relation to chalk streams (Section 3.4.1). Fundamentally, many proposed targets for sediment management in freshwater systems have been oversimplified through lack of consideration of variations in hydro-sedimentological responses across different river systems (Collins and Anthony, 2008). Importantly, existing sediment targets fail to recognise key mechanisms controlling fine sediment deposition and accumulation in gravel beds, including fine sediment inputs into a river network from the surrounding catchment and/or channel margins, transport of fine sediment in the water column as suspended load or bedload, infiltration of fine sediment into the gravel beds, and exfiltration of fine sediment from gravel beds (Section 3.5.1).

Robust and system-specific fine sediment management targets can in principle be established for chalk streams; however, three gaps in the current knowledge of the fine sediment problem in chalk streams must be addressed. Firstly, better determination of the gravel bed sedimentological characteristics, including quantity, distribution, and composition of fine sediment. Second, the significance of potential regional differences between the sedimentological characteristics of chalk stream gravel beds and whether these can be attributed to local superficial geology and/or catchment sediment sources/budgets. Third, the representativeness of current models of fine sediment infiltration in gravel beds and resulting management for conditions occurring in chalk streams. In the above context, robust sediment targets for chalk streams, are critical to improve guidance and management for achieving maintenance or restoration of ‘good ecological status' under the Water Environment WFD (England and Wales) Regulations 2017 (JNCC, 2021). Despite the well-documented need for improved management of the fine sediment problem, and the concomitant need for mechanistically-defined management targets (Collins et al., 2011; 2015; Collins and Zhang, 2016; Naden et al., 2016; Mondon et al., 2021), a novel thorough and holistic data synthesis and analysis has, until this present study, not been carried out for multiple chalk streams. As such, our objectives were to: (1) collate existing freeze-core sediment data from a sample of English chalk streams, including their tributaries; (2) using this data, describe their gravel bed sedimentological characteristics through metrics that link to the processes of bed structuring, fine sediment infiltration and channel bed saturation; and (3) investigate the representativeness of chalk stream sedimentology in models describing fine sediment/gravel bed interactions. In doing so we aimed to identify gaps in the spatial distribution of chalk stream sediment data and highlight critical areas for future research.

4.3 Background

Gravel beds are characterised by a wide range of particle sizes, typically exhibiting a bimodal GSD, comprising a framework fraction of coarser particles (gravels and cobbles, >2 mm) and a matrix fraction of finer particles (sand, silts, and clays, <2 mm) which occupy the interstitial spaces in the framework gravels (Carling and Reader, 1982; Petts and Thoms, 1986). These can be separated by a "saddle frequency interval" between 2 and 4 mm (Carling and Reader, 1982; Carling, 1983; Petts and Thoms, 1986). In a 'healthy' gravel bed, the substratum is permeable, with high rates of intra-gravel flow and dissolved oxygen availability, as finer particles only partially fill interstitial spaces in the framework. This is considered a *"framework-supported"* bed, with coarser particles in tangential contact and fines representing <30% of the bed weight (Carling and Glaister, 1987; Church et al., 1987; Bunte and Abt, 2001; Wilcock and Kenworthy, 2002; Frings, 2011). Classifications of gravel beds are largely based on the quantity and vertical extent of fine sediment. As quantities of fines increase, the proportion of coarse particles in contact reduces. If fines exceed 50% of the total bed weight, the bed is considered to be "*matrix-supported*" (Carling and Glaister, 1987; Church et al., 1987; Bunte and Abt, 2001; Wilcock and Kenworthy, 2002). Alternatively, the concept of a saturated fine sediment fraction (FSF) was introduced by Wooster et al. (2008), to quantify the maximum quantity of fines that can infiltrate a gravel bed before it is no longer considered "*framework-supported*". If this threshold is exceeded, the bed is described as *over-saturated* with fines and is either *partially framework-* or *matrix-supported*. A numerical model (4.1) was proposed by

Wooster et al. (2008) to determine this status, where the saturated FSF is a function of the GSD of the bed substrate and the infiltrating fine sediment, and the measured FSF of the given deposit:

$$f_s = \frac{0.621(1 - 0.621\sigma_{gg}^{-0.659})\sigma_{gg}^{-0.659}}{1 - 0.621^2(\sigma_{gg}\sigma_{sg})^{-0.659}}\ x\ \left[1 - \exp\left(-0.0146\frac{D_{gg}}{D_{sg}} + 0.0117\right)\right] \qquad (4.1)$$

where f_s is the saturated FSF, σ_{gg} and σ_{sg} are the geometric standard deviation for the framework sediment and infiltrating sediment, respectively, and D_{gg} and D_{sg} are the geometric mean of the framework (gravel) sediment and infiltrating fine sediment, respectively.

4.3.1 Development of gravel beds

Gravel riverbeds can develop via two mechanisms. Firstly, they can develop via the simultaneous transport and deposition of framework and matrix fractions. This requires high magnitude events that are capable of removing the surface armour layer and exposing the subsurface sediment to flow (Parker et al., 1982; Andrews and Parker, 1987). Secondly, gravel riverbeds can develop via the deposition of framework particles and subsequent infiltration of matrix particles (Fraser, 1935; Frostick et al., 1984). The infiltration mechanisms of fine sediment can be a controlling factor in the quantity and distribution of fine sediment and can be determined by the size ratio between infiltrating fine sediment and the bed framework (e.g., Beschta and Jackson, 1979; Diplas and Parker, 1985; Lisle, 1989).

In chalk streams, the occurrence of planform sinuosity appears to contradict the observations of limited stream power and limited lateral channel movement that are characteristic of chalk streams (Acornley and Sear, 1999; Sear et al., 1999; Mondon et al., 2021) and likely arose due to past hydrological conditions. Lowland river evolution in the UK started with relativity high energy systems (with braided and meandering planforms) during the last glaciation (Brown et al., 2018). These planforms became fossilised during the early Holocene by substantial fine sediment accumulation (Collins et al., 2006; Whiteman and Haggart, 2018), possibly associated with debris flows or hyperconcentrated flows from valley sides. Subsequent immobility of the fluvial gravels, and reduced supply from inactive valley slopes and low rates of bank erosion, suggests that chalk stream gravel beds are fossils, remnants that developed under higher energy conditions (Sear et al., 2006). Thus, suggesting that chalk stream gravel beds developed via the second mechanism, deposition of framework gravel and subsequent infiltration of matrix particles. The characteristics of chalk streams (e.g., low bed mobilising flows) limit bed material transport, encouraging fine sediment accumulation. Bed material transport is further limited in chalk streams by the upwelling of calcium rich groundwater, creating calcareous deposition (tufa), resulting in concretion of the framework and finer particles in the gravel bed (Acornley and Sear, 1999; Sear et al., 1999; 2006). Tufa formation can not only “concrete” immobile gravel beds but also forms a low-density bed and suspended sediment load via deposition of calcium carbonate ($CaCO_3$) tufa around leaf and twig fragments. These can breakdown into low density sand-sized fragments, that since they are of a lower density than silicate sands, can be transported by contemporary chalk stream flows and can form the dominant source of bed material transport (Acornley and Sear, 1999; Sear et al., 1999).

4.3.1.1 Investigations into fine sediment infiltration mechanisms

Numerous experimental studies have been carried out to determine the mechanisms of fine sediment infiltration into gravel beds and their resulting sedimentary characteristics (Table 4.1). An early study (Einstein, 1968) determined that sand-sized particles (0.02 mm) infiltrated into a clean gravel bed, filling the pores from the bottom upwards. Beschta and Jackson (1979) later observed that particles <0.5 mm infiltrated to a depth of ~10 cm (equivalent to twice the diameter of the coarsest bed material (50 mm)), and that finer particles (<0.2 mm) infiltrated deeper and accumulated in larger quantities; suggesting that the size ratio between the framework and infiltrating sediment is an important factor in the mechanics of fine sediment accumulation in gravel beds.

Table 4.1: Sedimentary characteristics of flume experiments used to investigate the mechanisms of fine sediment infiltration into immobile gravel beds (FZ – flume zone, D_{gg} & D_{sg} – gravel and fine sediment geometric mean, σ_{gg} & σ_{sg}– gravel and fine sediment geometric standard deviation (sorting coefficient)).

Experiment	*Run*	*Bed sediment (mm)*			*Fine sediment (mm)*	
		Depth	D_{gg}	σ_{gg}	D_{sg}	σ_{sg}
Einstein (1968)	1 – 5, 9 – 1		22.20	2.29	0.02	
	6 – 8		88.90			
Beschta & Jackson (1979)	1 – 18, 21	305	15.00	1.57	0.50	
	19, 20				0.20	
Carling (1984)	1 – 16	150	16.00	2.12	0.19	
	17 – 25	100			0.15	
Diplas & Parker (1992)	1 – 12		2.44	2.75	0.11	
	13 – 19				0.08	
Wooster et al. (2008)	FZ 1 & 10	120	7.20	1.87	0.35	1.24
	FZ 2		10.20	1.77		
	FZ 3		13.10	1.68		
	FZ 4		17.20	1.17		
	FZ 5		7.30	1.90		
	FZ 6		7.90	1.22		
	FZ 7		8.70	1.71		
	FZ 8		7.60	1.46		
	FZ 9		4.30	1.65		
Gibson et al. (2009)	1	100	7.10	1.37	0.43	1.70
	2				0.26	1.94
	3				0.21	1.55
	4				0.12	1.37
Gibson et al. (2010)	FZ 1	100	9.70	1.27	0.21	1.55
	FZ 2		7.20	1.39		
	FZ 3		6.00	1.19		
	FZ 4		5.30	1.24		
	FZ 6		3.70	1.25		
	FZ 8		2.90	1.10		
Gibson et al. (2011)	1	100	7.70	1.41	0.65	1.58
	2				0.36	1.66
	3		9.70	1.27		
Kuhnle et al. (2013)	1 – 30		35.00	1.15	0.30	
Dudill et al. (2017)	1		5.00		0.70	
	2				0.90	
	3				1.50	
	4				2.00	
	5				3.00	
	6				4.00	

The field study of Frostick et al. (1984) examined fine sediment infiltration into gravel beds with the same surface grain sizes but differing subsurface grain sizes; their observations indicated that more fine sediment infiltrated coarser subsurface deposits compared with finer deposits. Frostick et al. (1984) hypothesised that this was the result of lower surface to subsurface grain size ratios as opposed to infiltration and bed sediment ratios. Flume experiments by Diplas and Parker (1985) concluded that immobile gravel beds would eventually become saturated as long as fine sediment was available in the water column, irrespective of sediment load, supporting the findings of Beschta and Jackson (1979). Building on this, field experiments conducted by Lisle (1989), observed that fine sediment infiltration decreased with increasing sediment load and that coarser fine sediment clogged the surface layer of the bed, preventing further infiltration of fines. This outcome supported earlier theories that size ratio between infiltrating and bed sediment is a controlling factor in infiltration depth. Similar results were observed in other field studies (e.g., Carling, 1984; Schälchli, 1992).

4.3.1.2 Fine sediment infiltration mechanism models

Developing on from these observations (Table 4.1), Lauck (1991) established one of the first models to describe fine sediment infiltration processes into gravel beds; proposing that once fine sediment enters a bed, it either continues to move downwards or becomes lodged within the bed framework. Cui et al. (2008) went on to propose a model based on Lauck (1991), which predicted that the highest possible fine sediment quantity is an exponential decay function with depth into the bed. Implying that significant fine sediment infiltration only occurs to a limited depth. Similarly, Wooster et al. (2008) demonstrated (through experimental and model-based research), that sand infiltration only occurred to a depth equivalent to a few bed D_{50}, based on vertical fine sediment profiles.

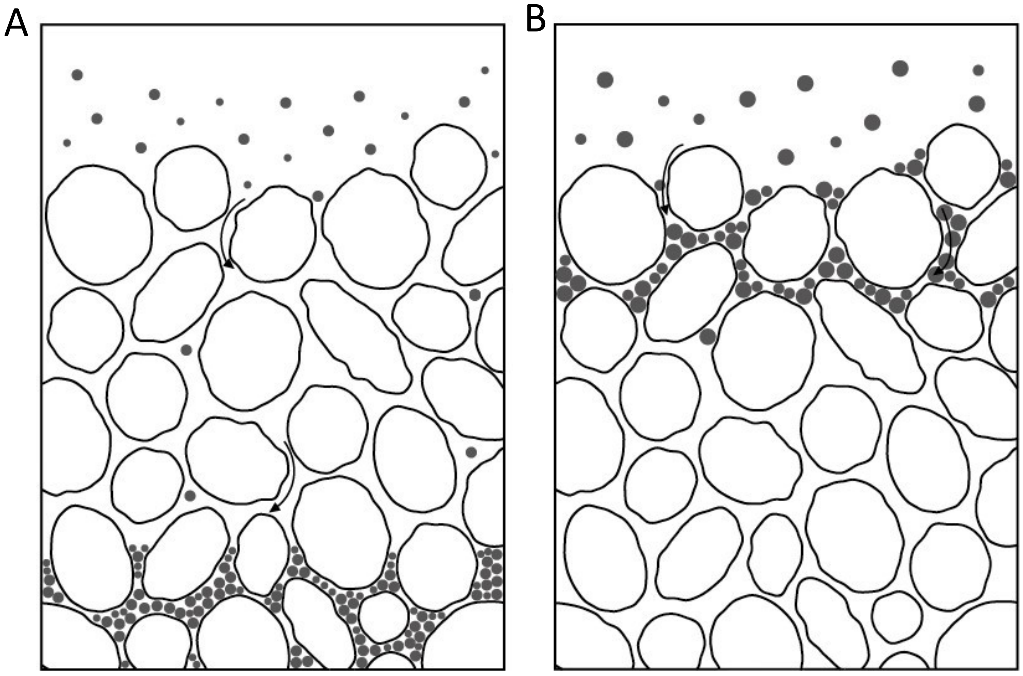


Figure 4.1: The two infiltration mechanisms observed in gravel beds, (A) unimpeded static percolation (USP) and (B) bridging (adapted from Gibson et al. (2009); Herrero and Berni, (2016)).

From these studies it was determined that fine sediment infiltrates immobile gravel beds via two mechanisms (Figure 4.1). The first is unimpeded static percolation (USP), whereby interstitial spaces within the bed framework are sufficiently large to allow infiltrating particles to percolate downwards, due to gravity and interstitial hydrodynamics, to an eventual impermeable layer and subsequently fill up bed pores over the whole depth. The second is bridging, whereby infiltrating particles are larger than the bed framework pore throats, trapping the infiltrating particles and forming a clogged surface layer protecting the underlying gravel framework from further fine sediment infiltration (Gibson et al., 2009; Herrero and Berni, 2016). Several models have been introduced to establish the occurrence of infiltration mechanisms, based on the grain size ratio between infiltrating and bed sediment. However, they are each compromised by several limitations and assumptions. Gibson et al. (2010) used flume experiments to determine a sand bridging threshold in static beds (Equation (4.2)):

$$12 < \frac{D_{15\,substrate}}{d_{85\,sand}} < 14 \tag{4.2}$$

where $D_{15\,substrate}$ is the framework particles size for which 15% of the particles are finer and $d_{85\,sand}$ is the sand-sized fine sediment particles for which 85% of the particles are finer. However, this threshold has been suggested to distinguish imperfectly between infiltration mechanisms (Herrero and Berni, 2016). Alternatively, Huston and Fox (2015) proposed an approach considering the ratio between the geometrical diameters of bed and infiltrating sediment, divided by the variance of bed GSD (Equation (4.3)):

$$\frac{D_{gg}}{D_{sg}\sigma_{gg}} > 27 \tag{4.3}$$

where, D_{gg} is the gravel (framework) particle geometric mean, D_{sg} is the fine sediment (matrix) particle geometric mean, and σ_{gg} is the gravel (framework) particle geometric standard deviation (sorting coefficient). However, neither of these models consider the influence of infiltrating sediment <62 µm, potentially overestimating D_{gg} and d_{85} values in the respective models. This could have substantial implications when considering natural environments with a high prevalence of silts and clays, potentially overrepresenting the occurrence of bridging. In addition, both models (1) make the assumption that particles arrive at pore throats one by one and (2) fail to consider occurrences of multiparticle bridging, which may be a function of the rate at which sediment infiltrates the bed (Valdes and Santamarina, 2008; Huston and Fox, 2015; Herrero and Berni, 2016). Given that there is a higher chance of coarser infiltrating sediment blocking framework pores compared with finer fractions, consideration of d_{85} by Gibson et al. (2010) compared with d_{sg} by Huston and Fox (2015), may be considered more appropriate. An alternative model was established by Schruff (2018), to determine the infiltration mechanism (Equation (4.4)):

$$d_u = \frac{D_{sg}}{\sigma_{sg}^{\ln(\sigma_{sg}^{1.5})}} \qquad D_u = \frac{D_{gg}}{\sigma_{gg}^{\ln(\sigma_{gg}^{1.5})}} \tag{4.4}$$

$$\frac{d_u}{D_u} < 0.11 - USP \qquad 0.11 < \frac{d_u}{D_u} < 0.32 - Finite\ depth\ infiltration \qquad \frac{d_u}{D_u} > 0.32 - Bridging$$

where D_u and d_u are the mean particle volume size for gravel (framework) particles and for the infiltrating fines sediment (matrix) particles, respectively. In contrast, to the previous models, this alternative model considers both the geometric mean and sorting coefficient of both the bed and infiltrating sediment. In addition, it considers the influence of infiltrating particles >62 µm and introduces finite depth infiltration. However, this equation has not been tested beyond the scope of the original publication nor against any experimental or field-based data.

4.4 Methods

4.4.1 Database of chalk stream study sites

All the streams investigated in this study are identified as chalk streams, based on the definition of rivers with a base-flow index (river flow derived from groundwater aquifers) exceeding 75% and a course which runs primarily over basal chalk geology (O'Neill and Hughes, 2014). Data on composition and structure of chalk stream gravel beds were collated from previous studies and reports. The main determinator of whether data were appropriate for this study was the inclusion of GSD and division of a sediment sample into a pre-determined number of size fractions. Subsequently, 12 UK based studies were found that satisfied this criterion, covering 122 sample sites across 14 chalk streams.

A variety of sampling techniques were used to collect gravel bed sediment and establish quantities of fine sediment, including, bulk sampling, freeze-coring and artificial redds. Both bulk sampling and artificial redds suffer from elutriation and winnowing of fine sediment by flowing water, which is not suitable given the need for detailed information on finer sediment fractions to accurately represent the entire gravel bed deposit. Subsequently, the freeze-coring techniques are more suitable: freezing of bed sediment and interstitial water in situ prevents fine sediment loss and vertical sections of substratum preserved by freeze-coring also allow for the determination of vertical variations in sedimentological characteristics. It should be noted, however, that there are a number of identified issues with freeze-coring techniques: (1) stratification of fine sediment within the bed can occur due to the insertion of the pipes into the bed; (2) if larger particles dominate the sample, the boundary layer can become irregular, creating bias; and (3) substantial variability can occur between samples, even within small sample areas, due to the typical size of individual cores (5 – 8 kg) (Beschta and Jackson, 1979; Lisle and Eads, 1991; Milan et al., 2001). The undertaking of multiple freeze-core within a sample site (ensuring reproducible results) has been demonstrated to minimise these issues (e.g., Thoms, 1992; Hughes et al., 1995). Despite the discussed issues, the advantages of freeze-coring techniques are more suitable for the present study and thus, data assembled using alterative techniques such as bulk sampling and use of artificial redds (e.g., Acornley and Sear, 1999; Heywood and Walling, 2007), were not considered further. In addition, a greater proportion of studies had used the freeze-core technique compared to other methods, thus creating a larger dataset for which to the determine the sedimentological characteristics of chalk stream gravel beds on. In order to best determine the natural sedimentological characteristics of chalk stream gravel beds, sites that had experienced any form of documented riverbed restoration, including gravel cleaning and/or the artificial augmentation of the framework particles, were also excluded from consideration. The overall dataset meeting these criteria, subsequently, comprised 90 sampling sites (Figure 4.2), encompassing 195 freeze-core samples, across 11 chalk streams (Table 4.2) and their tributaries, from 10 studies (Barron, 1982; Carling, 1983; Beaumont et al., 1993; Milan, 1994; Acornley, 1999; Riley et al., 1999; Greig et al., 2005a; Bateman, 2012; Mitchell, 2015).

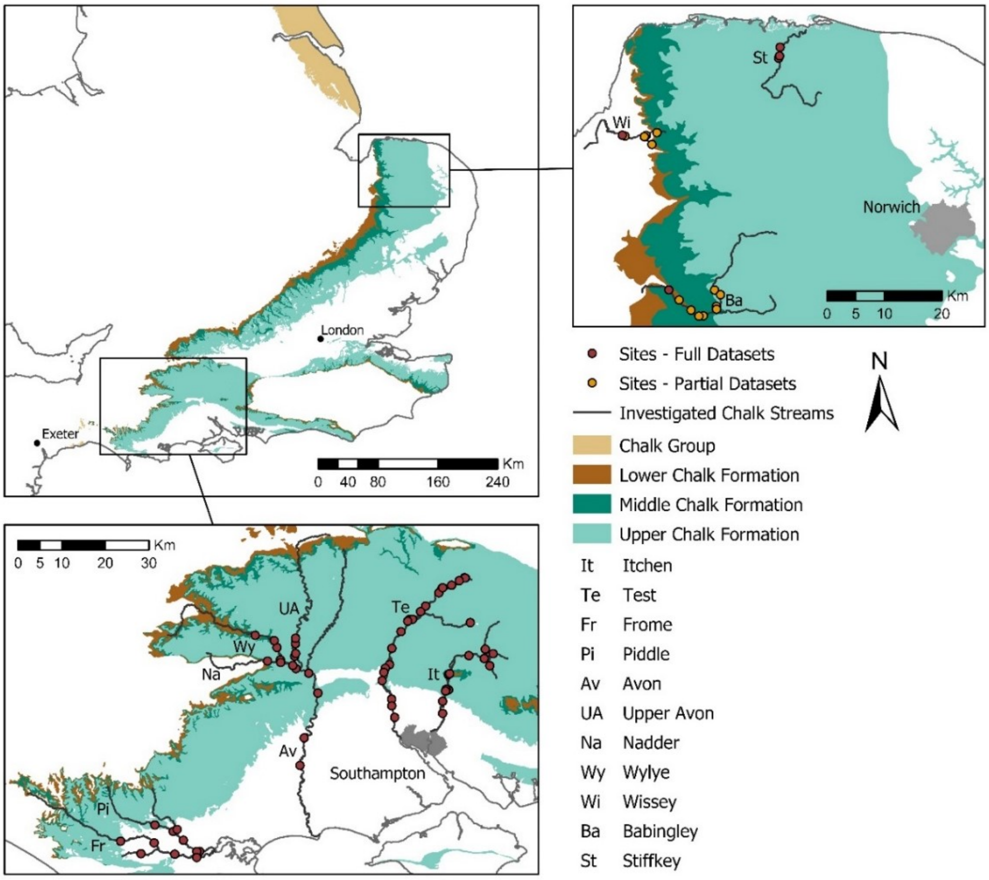


Figure 4.2: Location of the chalk stream gravel bed sampling sites included in this study.

An overview of the studies, including specific freeze-core sampling techniques, localised spatial distribution of samples and justification for the data collection is given in Appendix A.1. It should also be highlighted that the majority of original studies did not include information on the spatial distribution of freeze-core samples within channels. Consequently, the influence of this on the sedimentological characteristics of chalk stream gravel beds has not been established here. Studies ranged from the River Piddle in Dorset, South England, to the River Babingley in Norfolk, East England (Figure 4.2). The relevant data from each of these studies were extracted from grain size data tables and/or graphical readings of cumulative frequency curves from corresponding papers. Where available, data appertaining to the chalk stream physical characteristics were also extracted; however, where this was not stated, information was compiled from alternative sources (Table 4.2).

Table 4.2: Physical characteristics of the average site on each of the chalk streams and their associated tributaries investigated in this study.

Chalk stream	*Catchment area (km^2)*[a]	*Altitude (m)*[a]	*Width (m)*	*Depth (m)*	*Mean discharge (m^{3}s^{-1})*[b]	*Specific stream power (Wm^{-2})*
Itchen	119.60[c]	30.70	10.43	0.28[c]	4.60	8.76
Test	84.60	49.08	11.50		6.69	3.96
Frome	109.00	20.75	13.02		4.96	7.43
Piddle	37.80	18.80	8.27		2.02	8.98
Avon	111.50	29.30	21.88		15.08	4.27
Upper Avon	82.90	53.30	11.97		3.53	8.81
Nadder	43.60	52.30	11.61		2.89	13.43
Wylye	72.10	59.80	11.71		4.03	13.68
Wissey	76.10	15.20	8.79		1.90	2.62
Babingley	102.50	13.90	7.21		0.55	9.27
Stiffkey	99.07	9.00	6.60		0.58	7.23

a – Data derived from the UK Environment Agency River Catchment Data Explorer (EA, 2021: https://environment.data.gov.uk/catchment-planning).

b – Data derived from the UK National River Flow Archive for the period when the original investigation took place (UKCEH, 2022: https://nrfa.ceh.ac.uk/data/search)

c – Values provided in the published studies.

4.4.2 Data Analysis

GSDs based on the logarithmic Wentworth scale of particle sizes (Appendix A.2) were used to compare gravel bed sediments. GSDs were characterised by the following four distribution parameters: (1) the mean, central tendency of the distribution; (2) the sorting coefficient (i.e., standard deviation), spread of sizes around the average; (3) skewness, a measure of deviation from symmetry of a distribution; and (4) kurtosis, degree of concentration of grains relative to the average (Bunte and Abt, 2001). A range of cumulative percentile values (grain size for which the specified percentage of grains is coarser) such as the median particle size (D_{50}), were also used to compare bulk bed sediments. Several of the original investigations reported these parameters; unreported statistics were calculated using the mathematical ‘Geometric method of moments’ (Appendix A.3) in the Gradistat programme (Blott and Pye, 2001). In addition, to establish the potential influence of catchment and stream variables on quantities of fine sediment in the investigated gravel beds, the non-parametric Spearman’s correlation coefficient (r_s) was calculated, enabling the strength of any monotonic association to be quantified (Appendix A.4).

Results and observations from the selected field and experimental studies (Table 4.1) led to the determination of numerous metrics that can be used to infer various mechanisms of fine sediment infiltration and accumulation in gravel beds. Equation 4.1 was applied to determine whether the chalk stream beds in this investigation were under- or over-saturated with fines. Based on the limitations of the various models describing the infiltration mechanisms of fine sediment into immobile gravel beds, Equation 4.2 was deemed most suitable in this study. In the original determination of Equations 4.1 and 4.2, the gravel beds were initially void of fine sediment and the influence of fine sediment <62 μm was neglected. To achieve a similar representation of these conditions using the current dataset, the gravel bed GSDs were split into coarse particles (>2 mm), representative of bed substrate initially void of interstitial fine sediment and fine particles (2 mm > d > 62 μm), representative of fines >62 μm. Gravel bed structures were also described using the quantity of fine sediment as a proportion of the total bed weight; fully framework-supported (FFWS) (<20%), framework-supported (FWS) (20 – 30%), transition (T) (30 – 40%), matrix-supported (MS) (40 – 50%) and fully matrix-supported (FFMS) (>50%) (Carling and Glaister, 1987; Church et al., 1987; Bunte and Abt, 2001; Wilcock and Kenworthy, 2002; Frings, 2011). Finally, the determined sedimentary characteristics of chalk streams were compared with the conditions in flume experiments (Table 4.1), used to determine models describing the mechanisms of fine sediment infiltration and accumulation in immobile gravel beds.

4.5 Characteristics of gravel beds in the Chalk stream database

4.5.1 Gravel bed structure

A wide range of grain sizes were found in the chalk stream beds examined, from boulders (>128 mm in diameter) to clay (<3.9 μm in diameter). On the basis of statistical moments, chalk stream gravel beds on the whole may be described as very poorly sorted, finely skewed and mesokurtic to leptokurtic (Table 4.3); exceptions being the River Babingley and Wissey which can be described as symmetrical and highly platykurtic deposits; this is potentially explained by larger proportions of sand present in their gravel beds compared with the other chalk streams (Figure 4.3A). Average bulk D_{50} of the gravel beds was 13.95 mm (0.5 mm to 33.86 mm). All sites with a bulk D_{50} <10 mm (35% of sites), were present on the Rivers Babingley, Wissey, Itchen, Test or Stiffkey, apart from three sites on the River Wylye, two on the Upper Avon and one on the Piddle.

Table 4.3: Summary grain size statistics for average deposits (0 – 40 cm) of the chalk streams investigated, including the bulk (framework and matrix), framework (gravel) and matrix (fines) values (It – Itchen, Te – Test, Fr – Frome, Pi – Piddle, Av – Avon, UP- Upper Avon, Na – Nadder, Wy – Wylye, Wi – Wissey, Ba – Babingley, St – Stiffkey (See Figure 4.2), Ave – average, D_{50} – median particle size, D_g – geometric mean, σ_g – geometric standard deviation (sorting coefficient), S – skewness, K – kurtosis, $P_{2.0}$ – proportion of fine sediment <2 mm, P_{62} – proportion of fine sediment <62 μm).

Chalk Stream											
	It	*Te*	*Fr*	*Pi*	*Av*	*UA*	*Na*	*Wy*	*Wi*	*Ba*	*St*	*Ave*
Bulk (gravel & fines)												
D_{50}	9.80	6.22	22.48	17.78	15.60	21.25	16.61	15.67	5.71	4.54	6.26	13.95
D_g	5.68	4.31	20.27	14.22	7.60	13.53	10.44	14.70	2.99	1.82	4.42	10.20
σ_g	4.81	4.20	4.52	5.57	4.87	5.35	4.51	4.64	4.04	4.21	5.25	4.77
S	-0.95	-0.96	-1.36	-0.95	-1.19	-1.26	-1.39	-1.24	-0.20	0.29	-0.57	-1.11
K	3.22	3.49	3.91	2.78	3.46	3.62	4.34	3.79	1.48	1.58	2.31	3.46
$P_{2.0}$	27.72	34.70	16.32	23.49	19.22	19.12	14.95	18.69	45.14	51.63	35.69	25.17
P_{62}	7.00	15.21	0.71	0.93	1.34	1.57	1.50	1.57	3.90	6.90	10.04	4.52
Framework (gravel)												
D_{50}	14.96	10.89	26.82	24.89	19.87	26.80	20.32	19.47	23.02	20.37	12.58	19.67
D_{gg}	11.29	8.39	18.40	17.23	14.06	17.89	14.21	13.34	16.04	15.35	10.61	13.86
σ_{gg}	2.11	2.00	2.05	2.19	2.08	2.17	2.15	2.14	2.27	2.58	2.32	2.11
Matrix (fines)												
D_{50}	0.47	0.35	0.56	0.49	0.44	0.43	0.47	0.46	0.53	0.47	0.45	0.46
D_{sg}	0.36	0.25	0.51	0.46	0.41	0.39	0.42	0.41	0.33	0.31	0.34	0.39
σ_{sg}	3.44	4.49	2.03	2.04	2.16	2.36	2.40	2.39	2.10	1.93	2.42	2.78

The average chalk stream framework D_{50} was 19.67 mm (6.46 mm to 37.44 mm). However, unlike the bulk D_{50}, only the River Test was consistently lower, explained by a finer range of framework particles. All sites on the Test had >99% of the total framework consisting of particles <32 mm. Despite having low bulk D_{50}, the Rivers Babingley and Wissey, had frameworks consisting of coarser particles. All sites, however, had <60% of the total framework consisting of particles >32 mm (Figure 4.3A). The average quantities of matrix material as a proportion of total bed weight in in the investigated gravel beds was 25% (1% to 73%, dependent on site). Out of 195 gravel beds investigated, 28 (14%) had matrix proportions >40% of the total bed weight and can be considered as *matrix-supported* beds. All these sites were present on either the Rivers Babingley, Itchen, Stiffkey, Test, or Wissey. In addition, all sites on the Rivers Babingley and Wissey had quantities of fine sediment >30% of the total bed weight, suggesting that neither of these rivers have any *framework-supported* gravel beds. Notably, the Rivers Babingley, Wissey and Stiffkey had substantially higher quantities of medium sand (1 – 0.125 mm), >70% of the total fine sediment weight (Figure 4.3), compared with the River Itchen and Test at 42% and 31%, respectively. The River Itchen and Test, however, had higher quantities of silts and clays (>62 µm), 38% and 47% of the total fine sediment weight, respectively. Comparatively, the Rivers Babingley, Wissey and Stiffkey all had <15%. Conversely, 83 gravel beds (42%) had matrix proportions <20% of the total bed weight and can in this regard be considered *framework-supported* beds, with the River Nadder having the highest quantity (92%).

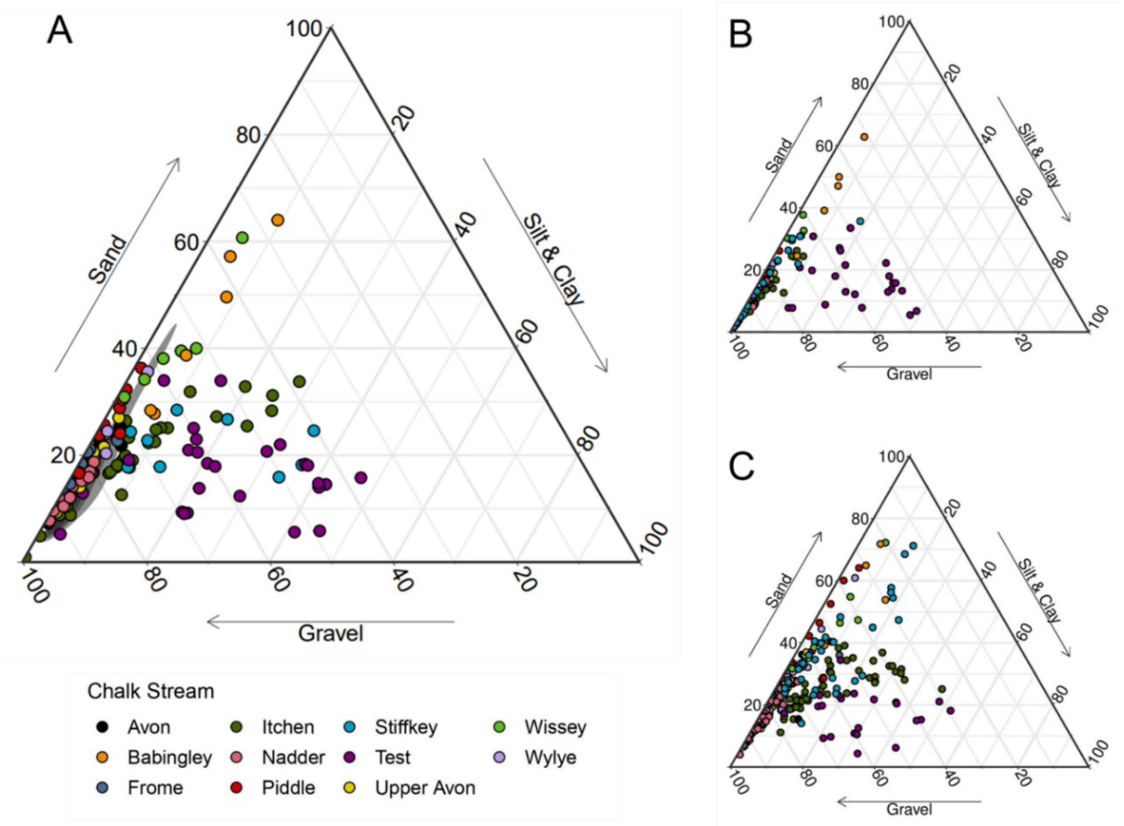


Figure 4.3: Percentages of gravel (d >2 mm), sand (2 mm < d > 62 μm) and silt and clay (d <62 μm) in chalk stream gravel beds in; (A) overall deposits (0 – 40 cm), (B) surface layers (0 – 10/15 cm) and (C) subsurface layers (10 – 40 cm). Points are grouped by individual chalk streams as depicted in the figure legend. Values from non-chalk stream gravel bed freeze cores are indicated by the grey region in (A) (Thoms, 1987; Lambert and Walling, 1988; Milan, 1996; Quin and Willams, 1999; 2000; Greig et al., 2005; Twine, 2013).

4.5.1.1 *Surface vs. subsurface*

Of all the gravel beds, 88% were characterised by a coarse surface layer (Table 4.4), with a higher bulk D_{50} and lower quantities of fine sediment in surface layers (0 – 10 cm) compared with subsurface layers (10 – 40 cm). The presence of a coarse layer can be quantified as the ratio between surface D_{50} and subsurface D_{50} (Bunte and Abt, 2001), defined as an armour ratio. The armour ratio varied across the chalk streams and was highest on the Rivers Babingley, Wissey and Stiffkey and lowest on the River Test, as evident from the minimal differences between the surface and subsurface GSD (Appendix A.5). All the other systems had a distinctive coarse-grained surface layer and a finer subsurface layer, and coarser bulk D_{50}.

Table 4.4: Bulk (framework and matrix) sediment characteristics for surface (0 – 10 cm) and subsurface (10 – 40 cm) layers in each of the chalk streams investigated (D_{50} – median particle size, D_g – geometric mean, $P_{2.0}$ – proportion of fine sediment <2 mm).

Chalk stream	*Surface (0 – 10 cm)*			*Subsurface (10 – 40 cm)*			*Armour ratio*
	D_{50}	D_g	$P_{2.0}$	D_{50}	D_g	$P_{2.0}$	
Itchen	14.46	7.39	19.86	6.99	4.12	40.26	2.07
Test	5.36	3.88	35.52	4.93	3.83	38.06	1.09
Piddle	26.78	30.06	11.53	16.56	14.15	27.21	1.62
Wylye	24.26	27.87	9.69	12.43	11.58	22.74	1.95
Frome	28.11	33.19	8.32	20.20	18.24	19.35	1.39
Avon	21.97	12.48	11.03	14.33	6.51	21.95	1.53
Upper Avon	26.99	21.77	12.09	19.41	12.29	21.96	1.39
Nadder	25.01	19.53	5.43	14.88	8.33	18.51	1.68
*Wissey**	11.23		33.08	2.78		54.85	4.04
*Babingley**	5.86		50.88	1.63		66.05	3.61
*Stiffkey**	15.15		20.29	5.21		46.20	2.91
Average	19.84	18.79	17.13	13.93	10.36	27.90	1.46

** D_g for the surface and subsurface layers were not given in the original investigations. Full GSDs were also not given for the surface and subsurface layers of the bed and therefore D_g for these systems could not be calculated.*

On average, the quantity of fine sediment as a proportion of the bed layer in surface layers was 17% (0.26% to 68%) (Table 4.4). However, omission of streams with larger quantities of fines (Itchen, Test, Wissey, Babingley and Stiffkey), reduces this average to 11%. In comparison, average fine sediment quantities as a proportion of the bed layer in subsurface layers were 27% (4.5% to 7%). The average increase in fine sediment between surface and subsurface layers was 58%. However, it was as high as 200% in some streams, such as the River Itchen. This trend was observed in all systems, apart from the River Test, where there was no marked difference, with fine sediment quantities averaging 30% in both surface and subsurface layers.

4.5.2 Vertical variation of fines

Vertical variations of fine sediment quantities illustrated an overall increasing trend with increasing gravel bed depth (Figure 4.4); increasing, on average, by 90% between surface (0 – 10 cm) and deepest subsurface layers (30 – 40 cm). Only three systems had an increase in fine sediment <50%; the Upper Avon (20%), attributed to the low quantities of fines (<25% of total bed weight) present in each bed layer and the Rivers Babingley (29%) and Test (7.5%), attributed to the high quantities of fines (>30% of the total bed weight) present in each bed layer. Highest increases in fine sediment quantities were observed between the surface (0 – 10 cm) and first subsurface layers (10 – 20 cm), averaging 98%; the Rivers Wissey, Babingley and Test are omitted as the original reports did not include data on the individual layers. Aside from the Rivers Avon, Upper Avon and Stiffkey, increases in fine sediment quantities between surface and subsurface layers were >100%. Increases in fine sediment quantities were less substantial between deeper bed layers (10 – 20 cm and 20 – 30 cm), averaging 13%. However, there was an average 15% decrease in fine sediment quantities in the deepest bed layers (30 – 40 cm), except in the Rivers Piddle and Stiffkey, which increased by 13% and 8%, respectively.

On average, the structure of the bed layers were either FFWS or FWS (71%), 14% were in T and 15% were either MS or FMS (Figure 4.4). The Rivers Nadder and Upper Avon had no occurrences of MS/FMS beds, whereas the River Wissey had only 7% FWS beds and the River Babingley had no beds that were FFWS or FWS, having 73% FMS. There was a general trend of increasing MS/FMS layers with increasing depth in the beds. An average of 9.5% of surface layers (0 – 10 cm, 0 – 15 cm on the Babingley and Wissey) were MS or FMS, compared with 19% of subsurface layers (10 – 40 cm). However, the proportion of bed structure changes differed greatly between streams. For example, 10% of surface layers (0 – 10 cm) in the River Stiffkey were MS and FMS, compared with 70% of the subsurface layers (20 – 30 cm). Comparatively, the River Wylye had zero MS/FMS surface layers (0 – 10 cm), 8% MS beds in the middle bed layers and zero in the deepest subsurface layers (30 – 40 cm).

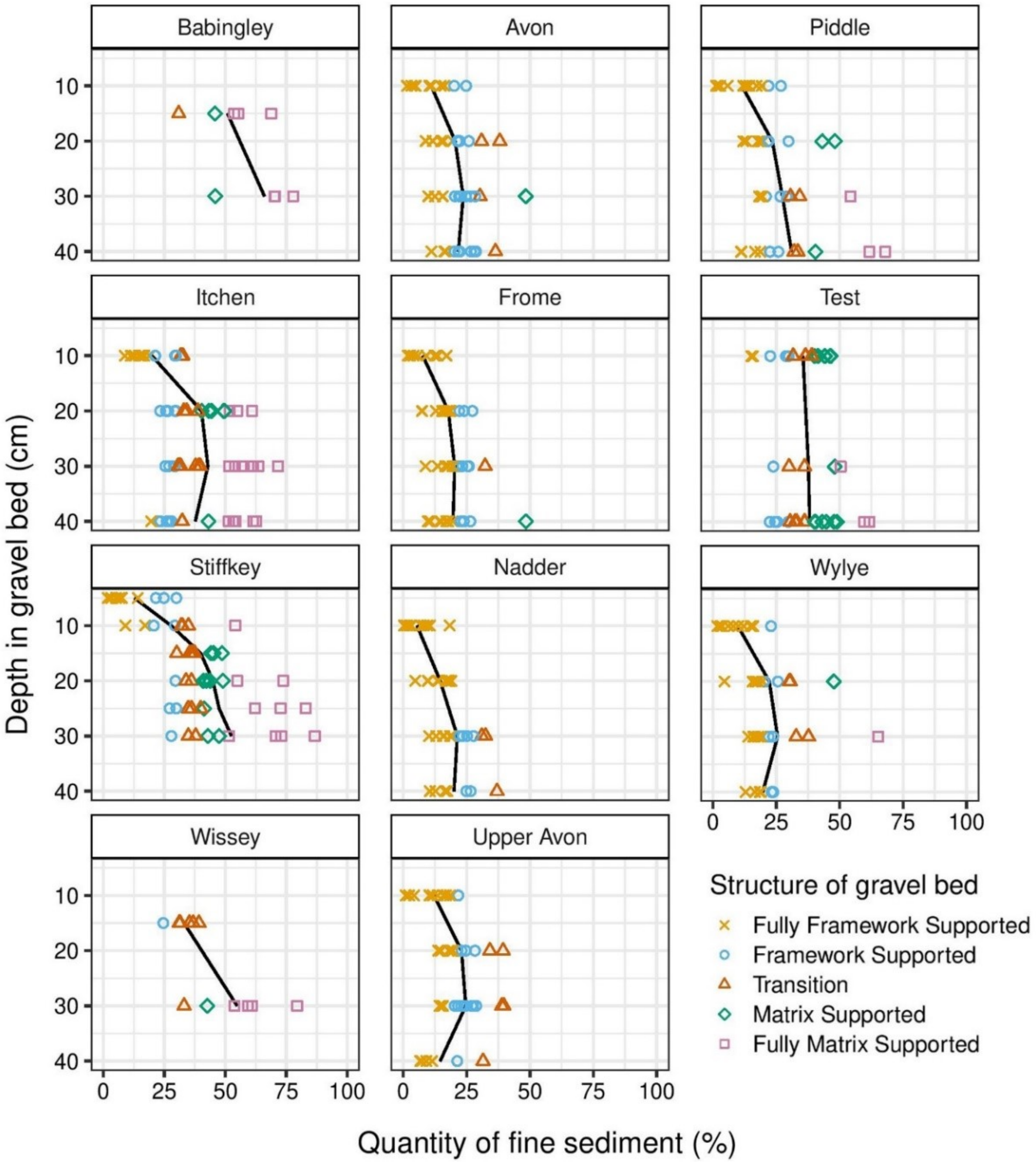


Figure 4.4: Quantities of fine sediment (<2 mm) as a proportion of individual gravel bed layers for each of the chalk streams. (Data are only shown where available for individual bed layers in the original investigations). Points are grouped by gravel bed structure, determined by quantity of fine sediment as a fraction of the total bed weight; fully framework supported (FFWS) (<20%), framework-supported (FWS) (20-30%), transition (T) (30-40%), matrix-supported (MS) (40-50%) and fully matrix-supported (FFMS) (>50%). Mean fine sediment proportions in each gravel bed layer are represented by the black lines.

4.5.3 Saturation of gravel beds

A greater proportion of gravel beds were over-saturated with fine sediment; 162 (89%) compared with 21 (11%) under-saturated beds (Figure 4.5A). Aside from the Upper Avon (27%), all the streams had <20% under-saturated beds. The Rivers Test, Stiffkey, Wissey and Babingley exhibited no under-saturated beds. When focusing on surface layers (0 – 10 cm) (Figure 4.5B) and subsurface layers (10 – 40 cm) (Figure 4.5C), a greater proportion of surface layers were under-saturated with fines (48%), compared with subsurface layers (10%) (the Rivers Stiffkey, Wissey and Babingley were omitted due to limited data in the original reports). The proportion of under-saturated surface layers ranged from 92% on the River Nadder to 28% on the River Itchen, whereas the proportion of under-saturated subsurface layers ranged from 21% on the Upper Avon to 3% on the River Wylye. The River Test had no occurrences of either under-saturated surface or subsurface layers and the River Itchen had no under-saturated subsurface layers.

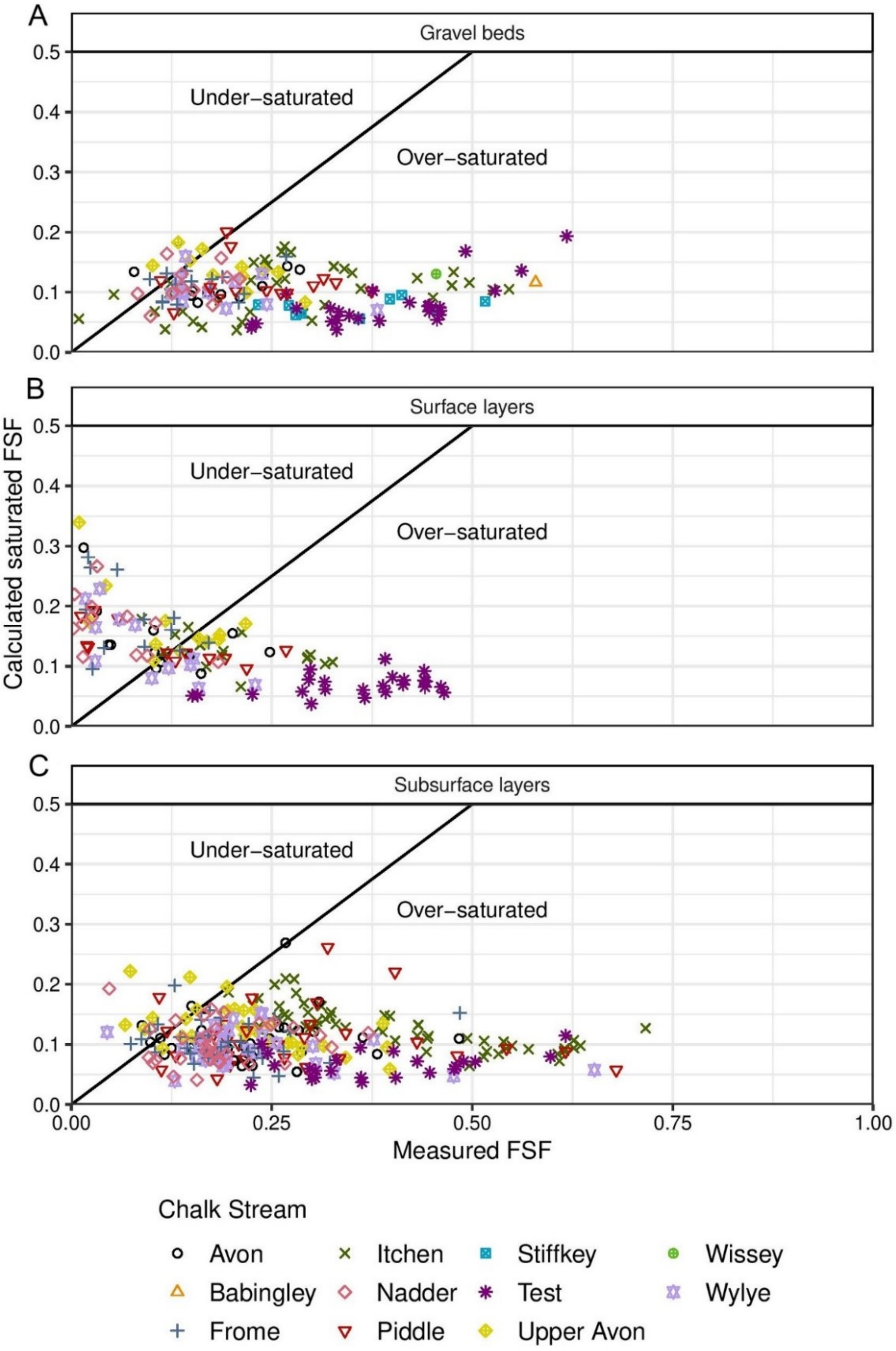


Figure 4.5: Comparison of calculated and measured FSF (fine sediment fraction) in; (A) chalk stream gravel beds (0 – 40 cm), (B) surface layers (0 – 10 cm) and (C) subsurface layers (10 – 40 cm). The equilibrium line represents a critical threshold of saturation, with gravel beds above the line under-saturated with fines and those beneath, over-saturated with fines. Points are grouped by chalk stream, as depicted in the figure legend.

4.5.4 The occurrence of infiltration mechanisms

The occurrence of infiltration mechanisms in the investigated chalk stream gravel beds was based on the application of Equation (4.2) and the GSD variables. Out of all the gravel beds investigated, 4.5% experienced USP or were in transition, where both USP and bridging are occurring (Figure 4.6; the Rivers Stiffkey, Wissey and Babingley were omitted due to limited data in the original report). All other gravel beds investigated experienced bridging. The occurrence of USP increased in the surface layers (0 – 10 cm), 14%, with an additional 6% in transition. This ranged from 33% in the River Frome to 7% in the Rivers Avon and Wylye. Both the Rivers Test and Itchen had no occurrences of USP in the surface layers, with 100% experiencing bridging. Bed layers experiencing USP decreases with increasing bed depth, with 6% of sites experiencing USP in the 10-20 cm layer, decreasing to 0% in the 20 – 30 cm layer. In contrast, bed layers experiencing USP increased in the deepest layers (30 – 40 cm), to 6%. However, a large proportion (87%) of overall deposits experiencing bridging were over-saturated with fines (Figure 4.6). In the surface layers, all beds experiencing USP (or in transition) were under-saturated with fine sediment and 63% of those experiencing bridging were over-saturated with fine sediment. The proportions of subsurface layers experiencing bridging and over-saturated with fine sediment were higher, i.e., >90% in the 10 – 20 cm, 20 – 30 cm, and 30 – 40 cm bed layers.

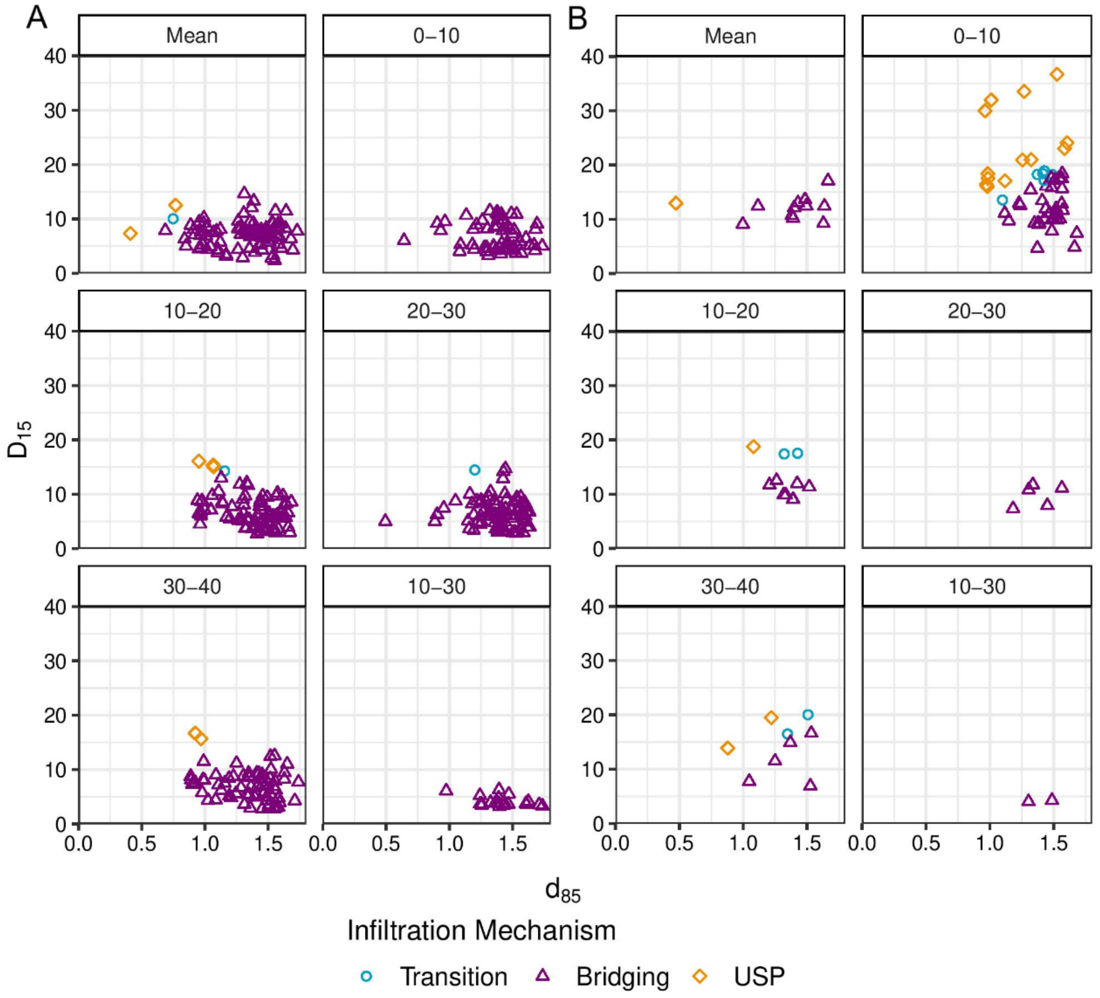


Figure 4.6: Occurrence of infiltration mechanisms in the chalk stream gravel beds investigated based on Equation (4.2), plotted by infiltrating fines d_{85} (excluding fine sediment <62 µm) and framework gravel D_{15}, by bed layers and mean deposits; (A) over-saturated beds and (B) under-saturated beds. Points are grouped by infiltration mechanism.

4.5.5 Field vs. experimental data

Comparison between the vertical distribution of infiltrating fine sediment in immobile gravel beds under experimental conditions with those found in chalk stream gravel beds (Figure 4.7), demonstrates contradictory trends in fine sediment quantities. The general trend in chalk streams is that of increasing fine sediment quantity with increasing bed depth, notably to 20 – 30 cm. In contrast, most experimental fine sediment distributions present with the highest proportions in the surface layers and decreasing quantities with increasing bed depth. This divergence can mostly be attributed to smaller framework GSDs used in experimental gravel beds. This outcome is supported by the fact most of the gravel beds under experimental conditions experienced bridging (Table 4.1) and that those where USP was observed had comparatively smaller infiltrating particles.

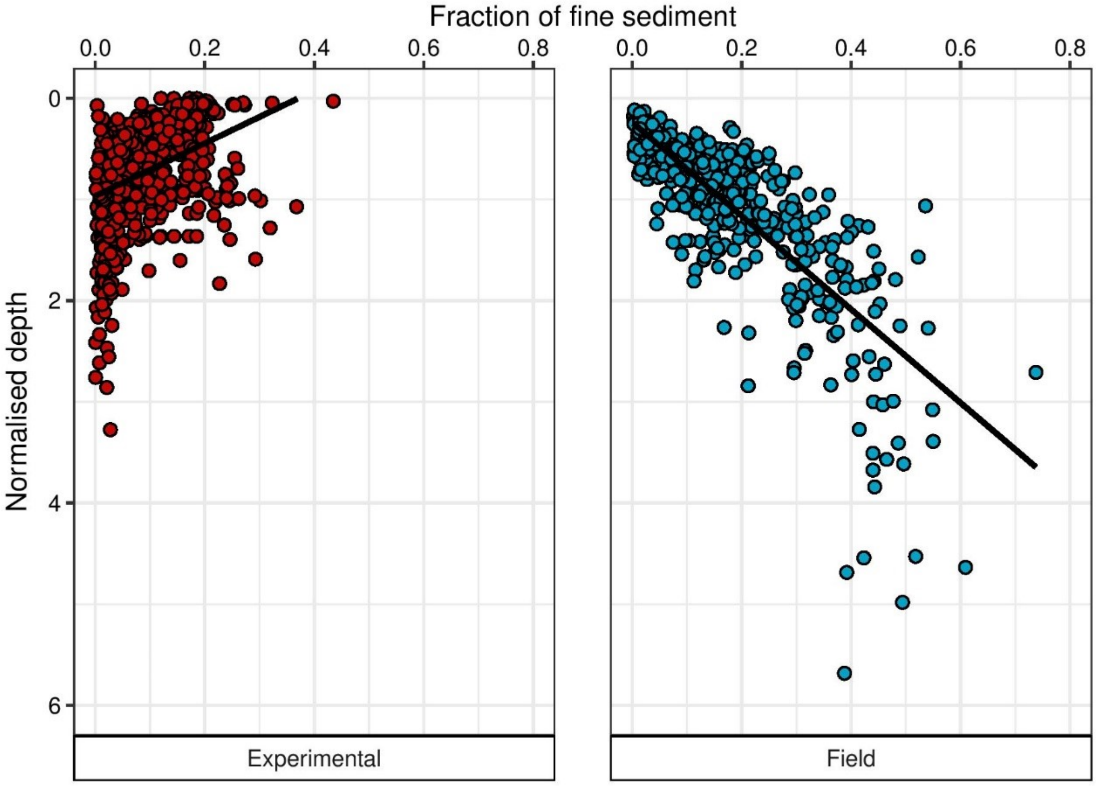


Figure 4.7: Vertical distributions of fine sediment quantities in chalk stream gravel beds (denoted by field data), compared with the results of fine sediment infiltration and accumulation experiments in immobile beds (denoted by experimental data), where data on fine sediment accumulation was available (Wooster et al., 2008; Gibson et al., 2009; 2010; Huston and Fox, 2015; Herrero and Berni, 2016; Núñez-González, 2016; Table 4.1). Depth of measurements has been normalised by the bulk D_{50} of each deposit, allowing for comparability between different depth profiles used in the original investigations.

The majority of experimental immobile gravel beds had a framework D_{50} of <10 mm, with only one experiment including a gravel bed framework with a D_{50} of >20 mm. In comparison, the average framework D_{50} for chalk stream gravel beds investigated in this study was 19.67 mm, including a number of frameworks with a D_{50} of >25 mm. There was, however, a greater representation of infiltrating particles sizes in published experiments, ranging from 0.02 – 4 mm, compared with those in chalk streams, which had an average matrix D_{50} of 0.42 mm. Infiltrating particles used under experimental conditions nonetheless had GSDs with sorting coefficients of well sorted to moderately-well sorted samples, indicating that there is very little variation in the grain sizes used. In contrast, the matrix fractions identified in chalk stream gravel beds were mostly poorly sorted to very poorly sorted, indicating high variation in the grain sizes present.

4.6 Discussion

Chalk stream gravel beds often have higher proportions of fine sediment compared with other types of gravel-bed rivers (Acornley and Sear, 1999; Collins and Walling, 2007b; Sear et al., 2008). This has been attributed to a combination of anthropogenic activities (e.g., expansive areas of winter cereal production on free draining soils) and the natural hydrological conditions within chalk streams (e.g., low bed mobilising flows). Despite this, current approaches to fine sediment management and targets have failed to address fundamental issues specific to the chalk stream fine sediment problem (Section 3.4.1). To determine the nature and extent of management requirements, knowledge of the current state and sedimentary characteristics of gravel beds (i.e., in relation to the distribution and quantity of fine sediment) is critical.

4.6.1 Chalk stream sedimentary characteristics and implications for modelling

The chalk stream gravel beds investigated in this study can be described as poorly sorted deposits characterised by a bimodal distribution consisting of a coarse-grained framework filled by a fine-grained matrix; fine sediments average 25% (±12.8%) of the total bed weight and in this regard the beds would be considered *framework-supported*. However, a large proportion of sites on the Rivers Itchen, Test, Babingley, Wissey and Stiffkey had fine sediment quantities >40% of the total bed sample and would be considered *matrix-supported*. Other UK gravel-bed systems have varying fine sediment quantities, but average values are towards the lower end of the range established herein for chalk streams (Table 4.3). For example, fine sediments accounted for 11.6% in highly flashy upland systems with low base flow indexes (Carling and Reader, 1982), 8.9% in the surface 20 cm of the River Exe, SW England (Lambert and Walling, 1988) and 15 – 19% in an urban section of the River Tame (Thoms, 1987). Chalk stream fine sediment quantities were found to increase with increasing depth in the gravel beds, with an average increase of 90% between the surface layers (0 – 10 cm) and deepest subsurface layers (30 – 40 cm). Gravel bed stratigraphy also reflected this, with *matrix-supported* layers becoming more prevalent with increasing depth. Aside from the River Test, all the chalk stream systems considered were characterised by a coarser surface layer (0 – 10 cm), with relatively small proportions of fine sediment (averagely 17%, Table 4.3). Despite this, infiltration mechanisms were dominated by bridging, attributed to the majority of these beds already being over-saturated with fines and therefore further infiltration of fines is inhibited. Furthermore, experimental conditions used to determine numerical models describing infiltration mechanisms (Table 4.1), do not represent the natural conditions observed in chalk streams. In the determination of numerical models, few experiments (e.g., three of the ten experimental runs used by Wooster et al. (2008)), used either gravel bed frameworks or infiltrating fine sediments with GSDs representative of those occurring naturally in chalk streams. GSDs used were often overly stylised, exhibiting for example, very well sorted, limited grain size, with very distinctively different fractions representing gravels and fines and often only considering the sand-sized fine sediment fraction (e.g., Gibson et al., 2011; Kuhnle et al., 2013; Dudill et al., 2017). Furthermore, the experimental gravel beds were often no more than 10 cm deep (Table 4.1), i.e., shallower than the 30 – 40 cm deep samples from chalk stream gravel beds. We conclude that the published *ex situ* experimental conditions reviewed in the present study are not representative of the GSDs typically found in natural chalk streams. Subsequently, models determined by these experiments have not been tested on the sedimentary conditions observed in chalk streams, and therefore, it cannot be confirmed how suitable these models are for describing the processes and mechanisms in chalk streams *in situ*.

4.6.2 Ecological suitability of gravel beds

Elevated quantities of fine sediment have been extensively demonstrated to affect freshwater organisms detrimentally, with a number of thresholds determined. For example, Heywood and Walling (2007) found that Atlantic salmon (*S. salar* L.) egg mortality was 100% when fine sediment quantities exceeded 14% of the total bed weight. Similarly, Greig et al. (2005a) reported 91.3% mortality of Atlantic salmon (*S. salar* L.) eggs when the proportion of fine sediment was 10% of the bed weight. Of all the chalk stream gravel beds investigated in the present study, 78% exceeded the 14% threshold (Heywood and Walling, 2007) and 95% exceeded the 10% threshold (Greig et al., 2005a). Some chalk stream biota have, however, been demonstrated to have a higher tolerance to excessive fine sediment quantities. For example, Bašić et al. (2019) demonstrated a 20% mortality of incubating European barbel (*B. barbus* L.) eggs for 10 – 40% gravel bed sand content; we note that consideration of only sand-sized particles removes the influence of the potentially most detrimental fraction of fine sediment i.e., silts and clays (<62 μm). Clay has been demonstrated to substantially reduce oxygen consumption by incubating salmonid eggs (Greig et al., 2005b). Neglecting the silt and clay fraction could potentially explain the observed lower mortality, despite the higher fine sediment quantity, in the case of European barbel (*B. barbus* L.) (Bašić et al., 2019). Other chalk stream species are intolerant of excessive fine sediment, including, Ephemeroptera (*Baetis rhodani*) (Wood et al., 2005; Larsen and Ormerod, 2010), Isopoda (*Asellus aquaticus*) (Wood et al., 2005), mayfly (Ephemeroptera) eggs (*S. ignita* P.) (Everall et al., 2018), white-clawed crayfish (*A. pallipes* L.) (Rosewarne et al., 2014), and Brown trout *(S. trutta* L.) (Berli et al., 2014). However, these studies only focused on suspended sediment concentrations, and it is therefore difficult to establish equivalent thresholds for gravel bed fine sediment.

Published studies have recognised that the surface 10 cm of chalk stream gravel beds are the most ecologically sensitive to excessive fine sediment. Higher macroinvertebrate species abundance and diversity has been found in the benthic (0 – 5 cm) zone than in the hyporheic zone (>20 cm) in many chalk streams (Davy-Bowker et al., 2006; Stubbington et al., 2015; Dunscombe et al., 2018; Bunting et al., 2021). In addition, lithophilic fish species spawn in the surface 0 – 10/20 cm of chalk stream gravel beds, including Brown trout (*S. trutta* L.) (Acornley and Sear, 1999; Milan et al., 2000; Louhi et al., 2008), European barbel (*B. barbus* L.), Grayling (*Thymallus thymallus* L.) (Fabricus and Gustafsson, 1955; Gonzci, 1989), European river lamprey (*L. fluviatilis* L.) and Brook lamprey (*Lampetra planeri* L.) (Maitland, 2003; Silva et al., 2015). Atlantic salmon (*S. salar* L.) have been found to spawn up 30 cm (DeVries, 1997; Milan et al., 2000; Collins et al., 2014). When considering the surface layers (0 – 10 cm) of the investigated chalk beds, the number of gravel beds exceeding the proposed thresholds by Heywood and Walling (2007) and Grieg et al. (2005), are 51% and 68% respectively. Although lower than total bed deposits, a substantial proportion (>50%) of chalk stream gravel beds would be deemed unsuitable for salmonid spawning on the basis of this assessment. It should be noted however, that the use of species-specific threshold values alone may not be entirely suitable. For example, salmonid redds have been recorded in gravel beds with fine sediment quantities >32% (Crisp and Carling, 1989). Consequently, future management and fine sediment targets should ideally focus on improvement of this near-surface (depth <10 cm) zone of chalk stream gravel beds.

4.6.3 Causes of excessive fine sediment

Regardless of the observed differences in the gravel bed sedimentological characteristics and fine sediment quantities in the investigated chalk streams, most gravel beds are over-burdened with fine sediment and exceed quantities that are detrimental to some ecological functioning. Fine sediment quantities in gravel beds have been shown to relate to a system's stream power (Sear et al., 2008; Naden et al., 2016; McKenzie et al., 2022). Similarly significant negative correlations ($p < 0.01$) were observed in this study between decreasing stream power and increasing quantities of fine sediment in the investigated gravel beds (Appendix A.4). Comparison between chalk streams and other gravel bedded systems in the UK (Figure 4.8) supports this with the former; characterised by the lowest stream powers and the highest fine sediment quantities. Examples include the River Nadder, which is characterised by lower fine sediment quantities and a flashier flow regime, attributed to the Upper Greensand geology of its headwaters, making it more responsive to rainfall events compared with other chalk streams, which have predominantly chalk headwaters (Barnsley et al., 2021). Similarly, the River Test has one of the lowest average stream powers and highest average fine sediment quantities. The small difference in fine sediment quantities observed in the Test's surface and subsurface layers is further evidence of low stream powers; the stream powers are likely to be insufficient to create near bed turbulence sufficient to remobilise even the finest surface sediment.

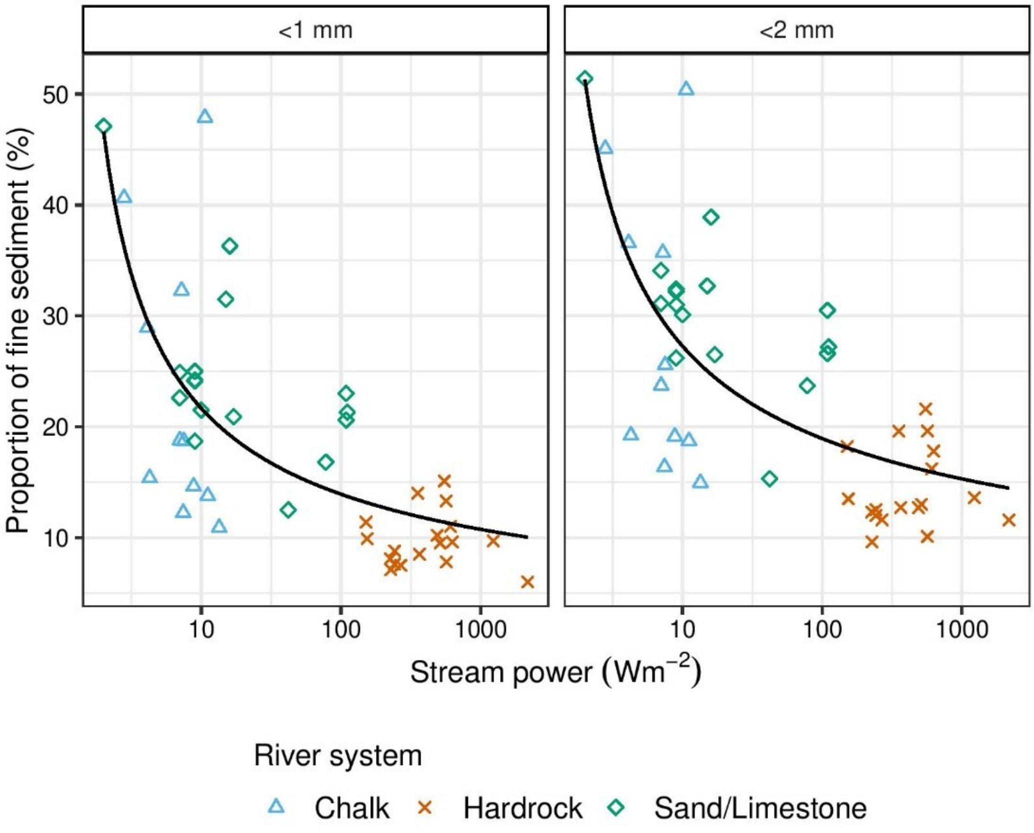


Figure 4.8: Average quantities of fine sediment (<1 mm and <2 mm) within the riverbeds of gravel bed river systems (Milan et al., 2000), compared with the systems stream power. Points are grouped by river system type.

Stream power does not, however, explain all the observed variations in fine sediment quantities across the investigated chalk streams. For example, the River Itchen has average stream powers closely comparable with the Upper Avon (8.76 and 8.81 Wm^{-2}, respectively). However, the River Itchen, on average, has higher proportions of fine sediment compared with the Upper Avon (27.71% and 19.12%, respectively), indicating other influencing factors. A proposed gravel bed sediment budget separates the controlling factors of fine sediment accumulation in chalk streams into four distinct overarching mechanisms (Section 3.5.1). Stream power heavily influences three of these mechanisms: transport of fine sediment in the water column; infiltration of fine sediment into the gravel bed, and; exfiltration of fine sediment from the gravel bed. Subsequently, the fourth mechanism, sediment supply to chalk streams, is most likely the key influencing factor leading to high levels of fines in combination with relatively low stream power. Sediment supply to river networks is controlled by local catchment conditions such as, sediment source (e.g., land-use and geology) and catchment-network connectivity

(Boardman et al., 2019; Upadhayay et al., 2022). For example, agricultural runoff is a main contributor to fine sediment inputs in chalk streams (e.g., Collins and Walling, 2007b, Collins et al., 2009; Zhang et al., 2014), with significant positive correlations ($p < 0.01$) observed in this study between increasing proportions agricultural land and increasing quantities of fine sediment in the investigated gravel beds (Appendix A.4). Therefore, the higher proportions of arable land within the River Itchen compared with the River Piddle (44% and 19%, respectively), potentially explain the elevated fine sediment quantities, most notably silts and clays (Naden et al., 2016). Agricultural inputs are potentially further reduced in the Piddle catchment due to the higher proportion of woodland (50% higher than the Itchen), which acts as a sediment trap, reducing both connectivity within a catchment and inputs into river channels (Pulley and Collins, 2021). The influence of sediment sources is also apparent in the Norfolk systems; however, these differ from the Dorset and Hampshire systems as they are predominantly influenced by local geology as opposed to the local land-use. Most notably, the easily erodible sandy soils in the catchments of North Norfolk; a consequence of ice marginal processes, in the Late Wolstonian age in the Babingley and Wissey catchments (Gibbard et al., 2018) and Late Devensian age in the Stiffkey catchment (Brand et al., 2002). The matrix material composition of the Norfolk chalk stream gravel beds supports this assertion, with these beds having substantially higher proportions of sand-sized particles than the Hampshire systems, which have larger proportions of silts and clays. Due to lack of available information in the original studies on the spatial distribution of freeze-core samples within channels, it was not possible to determine the influence of localised conditions on the sedimentological characteristics of chalk stream gravel beds and the quantities and distribution of fine sediment in this work.

4.6.4 Implications for sediment management

It is evident that both sediment-source and the transport capacity (stream power) of a system, influence chalk stream propensity to accumulate fine sediment. Therefore, management and targets that address both these issues are critical. Given that the majority of chalk stream gravel beds already have elevated proportions of fine sediment (i.e., 89% are over-saturated with fines as defined by Wooster et al., 2008) and that bed material is not naturally mobilised during bankfull events, then reducing fine sediment inputs will have little impact on the fine sediment already present. Specific stream power is a function of a systems discharge, slope, and width (Petit et al., 2005); therefore, to alter stream power at least one of these factors must be changed. Chalk streams are characterised by naturally low bed slope, which cannot be altered sufficiently to make substantial differences to specific stream power. Increases in chalk stream discharges are also not readily achievable, although they can potentially be managed by reducing abstraction from the chalk aquifers (Soley et al., 2012). Therefore, only the channel width of chalk streams can be efficiently altered with practical restoration and management techniques.

Nevertheless, for chalk streams to have stream powers similar to gravel bed systems where fine sediment quantities are consistently low (Figure 4.8), it would require channel width reductions to <1 m, which would be challenging to achieve. Therefore, alternative, and practicable approaches to management and restoration must aim for the same effects as reducing channel width but on a reach-scale, creating local patches of higher stream power. Approaches could include, for example, installation of large wood to generate localised regions of higher velocity, management of in-channel macrophytes to generate threads of high velocity flows, and removal of obstructions such as weirs (Gurnell et al., 2006; Heppell et al., 2009; Osei et al., 2015; Lenders et al., 2016; Parker et al., 2017; Gurnell and Bertoldi, 2022). Furthermore, such mitigation options are, arguably, readily achievable, and cost-effective. In addition, the introduction of large wood and aquatic macrophytes creates a heterogenous habitat within the gravel beds which is of enhanced ecological value, via fine sediment exfiltration through increased flows and via simultaneous sediment deposition in patches of slower flow (Cotton et al., 2006; Gurnell et al., 2006; Heppell et al., 2009; Osei et al., 2015). Areas of fine sediment comprise a key habitat for several protected chalk stream species such as the ammocoete stage of European river lamprey (*L. fluviatilis* L.) (Silva et al., 2015). Consequently, previous restoration approaches aimed solely at the removal of fine sediment instead of the restoration of hydrological and sedimentological processes, such as gravel washing (Pander et al., 2015), is highly detrimental for species that require this habitat, including lamprey for recruitment (Maitland, 2003). However, further research is required to determine to what extent these management and restoration techniques are required to reduce fine sediment quantities within the ecologically-sensitive surface 10 cm of chalk stream gravel beds, whilst also taking into consideration catchment-based sediment sources that will release material with different thresholds for erosion and deposition.

4.7 Conclusions

The results of this study confirm that the majority of chalk stream gravel beds are over-saturated with fine sediment. Although there are regional variations amongst English chalk streams, even systems with the lowest fine sediment quantities (i.e., Dorset) are exceeding critical thresholds for detrimental ecological effects. This in part can be explained by low stream powers precluding flushing of fines from stable gravel beds, and geological variations coupled with an increased supply of fines from intensive agricultural practices. Chalk stream gravel beds are therefore confirmed as sensitive to increases in fine sediment loads. As such, sediment targets designed to combat the problem of excessive fine sediment need to consider the generation of flushing flows, focusing particularly on the ecologically-sensitive surface 10 cm. To achieve this, management and restoration approaches could be used, including channel narrowing, management of instream macrophytes to produce narrow threads of unvegetated gravels, installation of large wood to locally narrow the river channel, and the removal of engineering impediments to flow (hatches, weirs etc.). Regional differences in the chalk stream fine sediment quantities also demonstrated the potential importance of sediment sources in controlling accumulation rates and highlights the need to consider sources in the management of fine sediment. However, further work is required to fill in the regional gaps highlighted (e.g., Thames and Kent regions) and to gain a greater understanding of the influence of localised channel conditions on the sediment characteristics of chalk stream gravel beds and the distributions and quantities of fine sediment. As both aspects could not be sufficiently assessed in the current work due to limitations/lack of available data in the original freeze-core studies. By extending our understanding of the sedimentary characteristics of chalk streams, the present study highlights the need for further research to establish the magnitude of flushing flows required to increase rates of fine sediment exfiltration. Importantly, our results highlight that current experimental data are not reflective of the natural conditions typically observed in chalk streams, bringing into question the representativeness of existing models derived from experimental data. If robust and scientifically based sediment targets are to be established, future work must address the representativeness of such models describing the interactions between gravel beds and infiltrating fine sediment.

Chapter 5 Remobilisation of fine sediment from chalk stream gravel beds under flushing flows

5.1 Abstract

Elevated fine sediment loads are known to cause substantial degradation to freshwater ecosystems. Chalk streams regularly exhibit substantially higher quantities of accumulated fine sediment within their gravel beds compared with other UK gravel bed river systems. This is a consequence of their natural flow conditions, most notably low bed mobilising flows. This characteristic in combination with their fine sediment-sensitive species, creates a high propensity for long lasting lethal/sub-lethal ecological impacts. Current approaches to management targets and targeted interventions have failed in chalk streams due to a lack of scientific knowledge underpinning them. Whilst research has quantified processes and magnitudes of fine sediment infiltration and accumulation in chalk stream gravel beds, none has been conducted on flushing of fines from within the riverbed. To address this gap, a series of progressive flume experiments were carried out to investigate the depths of mixed sized fine sediment (in particular, silt and clay <62 μm, identified has having substantial detrimental impacts on chalk stream biota) remobilisation from the ecologically-sensitive surface layer (0 – 10 cm) of a typical chalk stream gravel bed under differing flow conditions. The bed shear stresses of the experimental runs ranged from 0.6 to 8.1 Pa, with the increases in bed shear stress corresponding to increases in fine sediment cleanout depth. Patterns in the fine sediment quantities post-experimental runs, indicated two processes of fine sediment remobilisation that are important in keeping the surface layer of chalk stream gravel beds clean of excessive fine sediment: flushing of fines from the bed and hydraulic winnowing of fines within the bed. The new data were used to test the validity of previously proposed models for predicting fine sediment cleanout depths in gravel beds. Comparisons between observed and predicted cleanout depths demonstrated that these models mostly overpredict the cleanout depths; attributed to a number of assumptions within the existing models and a failure to consider the natural characteristics of gravel beds representative of chalk streams. The new data generated by this study can be used to help direct revised fine sediment targets, management and restoration activities and highlights that current models are unsuitable for use in chalk streams.

5.2 Introduction

Elevated quantities of fine sediment (inorganic and organic particles <2 mm) in the gravel beds of freshwater systems are known to cause substantial ecological degradation (Bilotta and Brazier, 2008; Kemp et al., 2011; Jones et al., 2012; 2017). These impacts are particularly evident in lowland systems with intensive agricultural catchments (Collins and Zhang, 2016; Naden et al., 2016); with 72-76% of fine sediment in UK river systems originates from agricultural sources (Collins et al., 2009; Zhang et al., 2014).

Chalk stream gravel beds have been shown to be particularly sensitive to elevated inputs of fine sediment due to their propensity to accumulate fine sediment (Section 3.3). The planform sinuosity of chalk streams contradicts their current hydrological conditions, which are characterised by limited stream power and lateral movement (Acornley and Sear, 1999; Sear et al., 1999; Mondon et al., 2021). The gravel bed and sinuous planforms of chalk streams are considered to be a relic of higher energy processes operating during periods when active periglacial or, in northern chalk streams, glacial processes were active; resulting from frozen soils and higher runoff (Brown et al., 2018; Whiteman and Haggart, 2018). Brown et al. (2018) and Sear et al. (2006) show that these former active sinuous braided channels were stabilised during the early Holocene by increasing groundwater-dominated hydrological regimes, vegetation colonisation and fine sediment accumulation in floodplains. Such conditions limit bed material transport and encourage fine sediment accumulation. These characteristics have been compounded by anthropogenic activities including increased connection to the surface of the catchment by underdrainage (in areas of mixed geology, such as clay), ditching, and construction of roads and farm tracks, that have increased sediment delivery and fine sediment loads (Sear et al., 1999). Channel widening, construction of weirs and hatches, and over-abstraction of chalk aquifers (reducing groundwater inputs) have also encouraged fine sediment deposition (Bickerton et al., 1993; Wohl, 2015; Grabowski and Gurnell, 2016). The result is a stable gravel bed into which fine sediments can accumulate at elevated rates.

Chalk stream gravel beds provide critical habitats for numerous aquatic species of national and international conservation importance including Atlantic salmon (*S. salar* L.), Brown trout (*S. trutta* L.), and Brook lamprey (*L. planeri* L.) (Section 3.3.3). They are naturally vulnerable to elevated levels of fine sediment (Mainstone, 1999; Mondon et al., 2021). However, analysis of fine sediment in 90 UK chalk stream gravel beds (Mondon et al., 2024; Section 4.6.2), found that 78% exceed the threshold for Atlantic salmon (*S. salar* L.) egg mortality proposed by Heywood and Walling (2007) and 91.3% exceed the threshold proposed by Greig et al. (2005a; 2005b). Elevated fine sediment accumulation alters the conditions in gravel beds via a number of mechanisms. These include the blocking of interstitial pores by silt and clay sized particles (<62 μm), which reduces intra-gravel permeability and porosity and limits rates of dissolved oxygen exchange (Sear et al., 2014; 2016; Wharton et al., 2017). In turn, this limits the transfer of resources between the surface and groundwater habitats, disconnecting the hyporheic zone from the benthic substrate (Mathers et al., 2014; Hartwig and Borchardt, 2015). The surface 10 cm of chalk stream gravel beds have been noted to be the most ecologically-sensitive to elevated quantities of fine sediment (Section 4.6.2). As a result, revised targets for the management of fine sediment in chalk streams need to focus on the removal of excessive fine sediment (particularly silt and clay sized particles <62 μm) from the surface 10 cm of the gravel bed, without the removal of the relict and naturally irreplaceable gravel framework.

The quantity of fine sediment within the gravel beds of rivers is controlled by four factors: A) inputs of fine sediment; B) the transportation of fine sediment; C) infiltration of fine sediment into the gravel bed, and; D) exfiltration of fine sediment from the gravel bed (Section 3.5.1). Numerous experimental flume studies have examined the transportation, deposition, and infiltration of fine sediment into immobile gravel beds (Einstein, 1968; Beschta and Jackson, 1979; Carling, 1984; Iseya and Ikeda, 1987; Schälchli, 1992; Wooster et al., 2008; Gibson et al., 2009; 2010; Kuhnle et al., 2013; Wren et al., 2014; Dudill et al., 2017; Mooneyham and Strom, 2018). However, there have been relatively few studies investigating exfiltration of fine sediment from immobile gravel beds (e.g., Grams and Wilcock, 2007; Kuhnle et al., 2015; 2016; Stradiotti et al., 2020; Trevisson and Eiff, 2022). Moreover, studies of exfiltration often fail to represent the natural conditions occurring in chalk stream gravel beds, with few experiments using either the GSD of the gravel bed frameworks or the infiltrating fine sediment found in chalk streams. Framework GSDs used in previous work were often overly idealised, with large distinctions between the fractions representing the gravel framework and interstitial fine sediment and/or very well sorted with a limited grain size (e.g., Grams and Wilcock, 2007; Trevisson and Eiff, 2022). Furthermore, most studies have focused on fine sediment in the sand-sized fraction; there are few examples where silt-clay sized sediment (<62 μm) was considered (e.g., Mooneyham and Strom, 2018; Stradiotti et al., 2020). Whilst some studies have considered fine sediment (<62 μm), these have done so within a framework consisting of sand-sized particles (e.g., Cunningham et al., 1987; Fetzer et al., 2017; Du et al., 2018) and are therefore equally unrepresentative of natural conditions in chalk streams. Importantly, wide GSDs of fine sediment similar to those observed in rivers (including sand, silt, and clay) have not been investigated in a flume study. Subsequently, this brings into question the reliability of the use of previous experiments for fine sediment modelling in chalk streams and the resulting uncertainties this may generate for established models and river management decisions.

Studies on the exfiltration of fine sediment from gravel beds have proposed models to predict maximum cleanout depths of fine sediment, in an attempt to help inform restoration and management techniques in degraded freshwater systems. Detert and Parker (2010) proposed a model to estimate washout depths of sand, based on the experimental data from Detert et al. (2010) study of flow and pressure fluctuations above, and within, a gravel bed (median grain diameter, D_{50} – 10.2 mm and 25.4 mm). Equation (5.1) describes this model:

$$\frac{\lambda_c}{k_s} = -1.0 \ln(\frac{u_*}{v_f}) \tag{5.1}$$

where λ_c is the cleanout depth of sand from the top of the gravel, k_s is the Nikuradse sand-equivalent grain roughness (skin friction), u_* is the shear velocity of the flow, and v_f is the fall (settling) velocity of sand. The Detert and Parker (2010) model assumed that the threshold of erosion occurred when the fine sediment fall velocity equalled the shear velocity and that bed roughness was a function of the bed median grain diameter. Kuhnle et al. (2016) tested this model using data from their flume experiments and concluded that it did not accurately predict cleanout depths of fine sediment, attributing this outcome to issues arising from the model assumptions. Other values for grain roughness were assessed, but no values were found to uniformly improve cleanout depth predictions.

Aiming to improve the representation of grain roughness in the Detert and Parker (2010) model, Kuhnle et al. (2015; 2016) proposed an alternative model based on the cumulative probability distribution of the gravel bed (CPDG) surface elevations, combined with a representative grain size to predict the cleanout depths of sand-sized particles (D_{50} – 0.2 mm, 0.3 mm and 0.86 mm) from an immobile gravel bed (D_{50} – 36.1 mm, sorting coefficient – 1.17) (Appendix B.1). CPDG and representative grain sizes have been demonstrated to scale bed surface shear stresses to the shear stresses in the upper layer pores of a gravel bed (e.g., Pellachini, 2011). Sand transport above an immobile bed has been previously predicted using bed shear stress multiplied by the CPDG (Kuhnle et al., 2013; Wren et al., 2014). Subsequently, Kuhnle et al. (2016) found that their CPDG model efficiently predicted cleanout depths of sand-sized fine sediment for their flume experiments, but it was not tested on cleanout depth measurements from other studies. Building on this study, Stradiotti et al. (2020) proposed a model for erosion rate and the maximum depth of fine sediment erosion from a gravel bed, based on their study of erosion rates of fine particulate bakelite (an artificial plastic particle, D_{50} – 0.45 mm) from a stable gravel bed (D_{90} – 30.44 mm). Unlike the Kuhnle et al. (2016) study, where fine sediment elevations were measured after each flume run, Stradiotti et al. (2020) adopted a laser line/video camera technique to take direct and continuous measurements of fine sediment erosion from the gravel bed. They proposed an approach relating the maximum cleanout depth of fine sediment, as a function of the shear velocity at the gravel crest (Appendix B.2). Their model was calibrated using data from their study and from Kuhnle et al. (2016) but was not validated using any additional experimental data.

The overall aim of this chapter was to collect data on the cleanout depths of mixed size fine sediment, with specific focus on silt and clay sized particles <62 µm in diameter, from a typical chalk stream gravel bed under a range of flow conditions. The series of progressive experiments were undertaken in a flume with a gravel bed representative of a typical chalk stream gravel bed, the GSD of which was determined using freeze-core data from 90 chalk stream field sites (Section 4.5.1; Appendix B.3). The experimental set-up was then used to develop and improve understanding of the relationship between chalk stream flow parameters, gravel beds and fine sediment cleanout depths. These data were then used to test the validity of the previously proposed models by Kuhnle et al. (2016) and Stradiotti et al. (2020) in predicting the cleanout depths of fine sediment (particularly, silt and clay sized particles <62 µm) from a chalk stream gravel bed framework.

5.3 Methods

5.3.1 Experimental set-up

Experiments were conducted in a 5 m-long by 0.3 m-wide by 0.45 m-deep, tilting straight recirculating flume channel located at the Sediment Dynamic Lab, University of Southampton, UK. The 0.16 m thick immobile chalk stream gravel bed began 1.35 m downstream of a honeycomb baffle block flume at the end of a header tank, and continued downstream for 2.2 m, ending 1.35 m upstream of the tailgate (bottom hinged weir; flume design; Figure 5.1). The initial and final 1.35 m of the gravel bed set-up consisted of a 1 m long slope and 0.35 m section of gravel bed with a generic GSD. These were installed to generate a fully mixed 3D flow over the bed and trigger the early development of the rough boundary layer. The experimental flow and turbulence conditions thus represented a more natural river condition and were not a product of the pumps and input structure of the flume. The gravel bed depth was chosen on the basis that the surface 10 cm of chalk stream gravel beds are the most ecologically-sensitive to elevated quantities of fine sediment (Section 4.6.2).

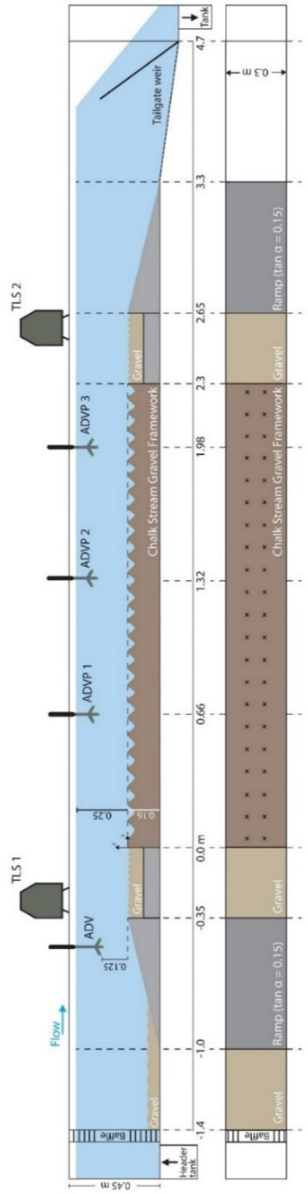


Figure 5.1: Experimental flume design, detailing the location of the chalk stream gravel bed and sampling points for the TLS (Terrestrial Laser Scanner), ADV (Acoustic Doppler Velometer), and ADVP (Acoustic Doppler Velometer Profiler). Fine sediment elevation measuring points are indicated by x points.

The GSD of the artificial chalk stream fine sediment fraction (Figure 5.2A) and gravel bed framework (Figure 5.2B) were calculated as the mean of GSDs from 90 gravel bed freeze-coring sites from 11 chalk streams across the UK (Section 4.5.1; Appendix B.3). The artificial chalk stream gravel bed framework consisted of quarry-sourced particles with a D_{50} of 19.8 mm and a sorting coefficient of 2.95. The desired GSD was prepared by weighing and sieving of the appropriate sizes. The fine sediment fraction, consisted of quarry-sourced sand (2 mm $<d<$ 0.125 mm) and fine sediment (d <0.125 mm) collected from the River Itchen (a chalk stream in southern England, UK; UK National Grid Reference SU 56461 31777, 51°04’57”N 001°11’43”W), which had a D_{50} of 0.32 mm and a sorting coefficient of 2.8. The fine sediment fraction was pre-mixed with the gravel bed particles and placed simultaneously into the flume (Figure 5.3A & B).

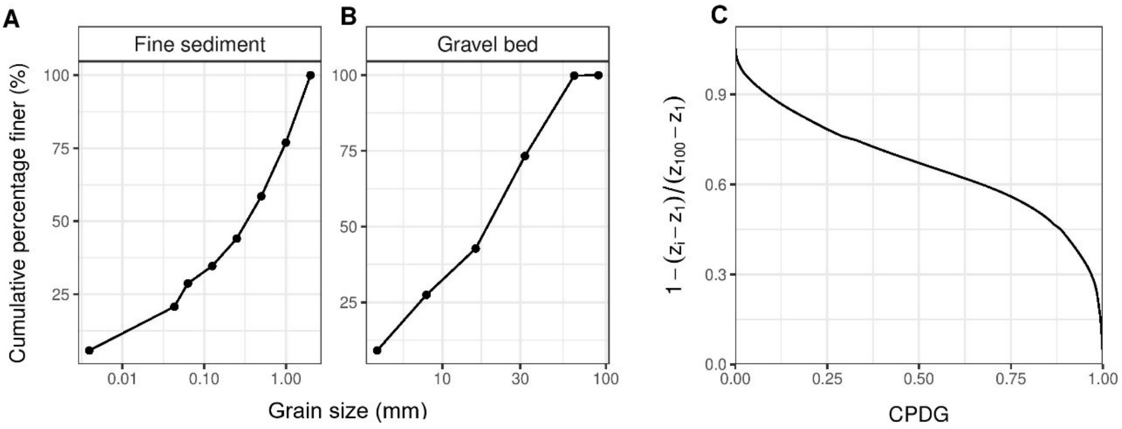


Figure 5.2: Sedimentary characteristics of the artificial chalk stream gravel bed used in this study; (A) the GSD of the fine sediment, (B) the GSD of the artificial gravel bed, and (C) the CPDG of the gravel bed surface substrate (Z_{100} is the elevation at the top of the highest bed particle and Z_1 is the elevation of the CPDG for which 99% of the particles are higher).

Figure 5.3: The artificial chalk stream gravel bed set-up in the experiments from (A) above and (B) the side of the flume.

After the initial artificial gravel bed set-up, a digital scan of the surface elevations was carried out using a Leica ScanStation P20 terrestrial laser scanner (TLS), mounted on top of channel rails at two cross-sections (Figure 5.1). Scans were conducted at an average distance of 1 m from the instrument to the bed, with an estimated laser spot size of 3.1 mm. Bed scans were repeated after each of the runs once the flume had fully drained so that water on the surface on the bed did not disrupt the scan (example of TLS scan of bed; Appendix B.4). Following the procedure by Kuhnle et al. (2016), these scans were used to calculate the cumulative probability distribution of the elevations of the gravel, which were scaled by the thickness of the surface roughness layer (Equation (5.2)):

$$\widetilde{Z}_i = 1 - \frac{Z_i - Z_1}{Z_{100} - Z_1} \tag{5.2}$$

where Z_{100} is the elevation at the top of the highest bed particle, Z_1 is the elevation of the CPDG for which 99% of the particles are higher, and $Z_{100} - Z_1$ represents the roughness geometry thickness (RGT). The CPDG of the gravel bed used in this study is shown in Figure 5.2C. The experimental runs were carried out under sediment supply-limited conditions, whereby there is no upstream fine sediment feed and eroded sediment was collected in a settling tank beneath the flume's weir, thus stimulating flow conditions within a natural chalk stream where fine sediment mobility only occurs during higher flows (Walling and Heywood, 2006; Grieg et al., 2007).

Flow depth in the runs was maintained by regulating the weir at the downstream end of the flume and pump speeds. Flow depths ranged from 0.25 m to 0.1 m (dependent on the run, Table 5.1) and were calculated as the difference between the height of the bed and the water surface at each of the cross-sections. Water-surface slope was calculated for each run using the distance between the water-surface and the top of the flume. Average outflow velocity (upstream) was measured four times in each experimental run by a downward-looking, 1.1 MHz Nortek Vectrino Acoustic Doppler Velocimeter (ADV), sampling a 7 mm cylindrical volume (single point) at 25 Hz, at the ADV location. Velocity profile data were collected twice at three positions (Figure 5.1) in each experimental run, by a downward-looking 1.1 MHz Nortek Vectrino Acoustic Doppler Velocimeter Profiler (ADVP) positioned in the centre of the channel. The ADVP sampled a 30 mm profile at 25 Hz (1 mm resolution) for 60 seconds, at four elevations in the water column, 0.20 m, 0.15 m, 0.10 m, and 0.05 m, to construct a full vertical velocity profile. Fine sediment (silt and clay fraction, <62 μm) elevations in the bed were measured manually (based on visual differences in the sand and silt and clay fractions) after each experimental run, at the points denoted in the flume design (Figure 5.1). The cleanout depths for each experimental run were calculated as the average of these measurements. Where necessary, surface gravel particles were temporally moved to allow for the measurement of the interstitial fine sediment and re-placed afterwards.

Suspended sediment samples were taken hourly during each experimental run and averaged for each, to give a suspended sediment (<1 mm) GSD for each experimental run. Each experimental flume run was carried out for 8 hrs, due to laboratory access restrictions. After the completion of the final run, samples of the interstitial fine sediment

(<1 mm) present in the gravel bed were taken at each of the fine sediment elevation measuring points at three depths within the bed: surface layer (0 – 5 cm), middle layer (5 – 10 cm) and subsurface layer (10 – 16 cm). A Malvern Mastersizer 3000 laser diffraction particle size analyser was used to measure the GSD of the suspended sediment samples and interstitial fine sediment samples (<1 mm). The average setup and conditions for each of the experimental runs are shown in Table 5.1. It should also be noted that each experimental run was done progressively, instead of independently, and eroded fine sediment was not restored to original quantities within the bed framework after each experimental run. Although, increasing exposure of the gravel bed particles will have an influence on observed patterns of bed shear stress, the outlined approach followed the procedure by Kuhnle et al. (2016). This was done in order to test the validity of the previously proposed models in predicting cleanout depths of mixed size fine sediment (particularly, silt and clay sized particles <62 μm).

Table 5.1: Average conditions during each of the experimental flume runs. Calculation of shear velocity is based on Equations (5.3 and 5.4).

Run	*Water surface slope (m)*	*Flow depth (m)*	*Flow velocity at water depth midpoint (m s^{-1})*	*Shear velocity (m s^{-1})*	*Bed shear stress (Pa)*	*Cleanout depth (m)*
Run 1	0.00120	0.25	0.2135	0.0240	0.580	0.0109
Run 2	0.00130	0.25	0.2494	0.0321	1.032	0.0134
Run 3	0.00135	0.25	0.2592	0.0357	1.275	0.0168
Run 4	0.00150	0.23	0.2827	0.0550	3.060	0.0222
Run 5	0.00200	0.20	0.3269	0.0624	3.925	0.0285
Run 6	0.00230	0.18	0.3301	0.0640	4.112	0.0347
Run 7	0.00270	0.15	0.3471	0.0819	6.728	0.0476
Run 8	0.00310	0.10	0.3214	0.0766	5.875	0.0428
Run 9	0.00340	0.12	0.3732	0.0915	8.078	0.0648

5.3.2 Data Analysis

ADV and ADVP data were processed in MatLab. The ADVP measured the 3D instantaneous flow velocity field (in 30 mm profiles) at four discrete points above the bed (0.20 m, 0.15 m, 0.10 m, and 0.05 m). The flow velocity field represents the streamwise (U, along the flume), the crosswise (V, transverse along the flume) and the vertical (W, positive upwards). Extraction of the turbulent fluctuations from the processed velocity components by Reynolds decomposition followed the approach detailed in Kassem et al. (2015; 2020). This included a quality check, whereby no more than 20% of a record falls below the correlation threshold, set at 70%, following the approach by Elgar et al. (2005). This is done to account for any noise arising from signal aliasing. A zero-phase moving average algorithm was then applied to replace values falling below the threshold by interpolation (Thompson et al., 2012). Signals were de-spiked using the 3D phase-space method by Goring and Nikora (2002; 2003), as modified by Mori et al. (2007). An axis-rotation algorithm was applied to the data to ensure alignment with the flow, eliminating the effects of sensor misalignment (Elgar et al., 2001). The data were then zero-meaned, de-trended and the mean U calculated from the three components. Resulting mean (time-averaged) vertical velocity profiles were extracted for each of the ADVP recordings, generating 180 velocity profiles in total. These were then averaged and combined to give three (one for each ADVP recording location) average velocity profiles for each experimental run (Appendix B.5). Using the average velocity profiles from each experimental run, the shear velocity u^* was calculated using the law of the wall equation (von Karman, 1930). This states that the average velocity of a turbulent flow at a certain height is proportional to the logarithm of the distance from that point to the “wall” (Equation (5.3)):

$$\bar{U} = (u^*)\frac{1}{k}\ln\left(\frac{h}{z_0}\right) \tag{5.3}$$

where $\bar{U}$ is the average velocity at given height (h), u^* is the shear velocity, k is the von Karman’s constant (k=0.4), h is the height above the bed and z_0 is the bed roughness. Linear regression was used to obtain these parameters, from the logarithmic velocity profiles, z_0 is thus defined as the intersection of the best-fit of the semi-log plot of depth and velocity where z_0 is the elevation at which velocity is reduced to zero. Using the shear velocity (u^*), Equation (5.4) was then used to calculate the bed shear stresses for each experimental run:

$$\tau_0 = \rho u_*^2 \tag{5.4}$$

where p is the density of water (1000 kg m^{-3}) and τ_0 is the bed shear stress. The resulting parameters from these calculations are shown in Appendix B.6. The decision was taken to determine bed shear stress estimates using the logarithmic profile method as opposed to single measurements of flow velocity for two key reasons: (1) no independent estimate of the roughness height is required to determine the shear velocity; and (2) the coefficient of determination (the R^2 value) gives a measure of the goodness of the fit for the data (Wilcock, 1996; Petrie et al., 2010). In addition, other methods to determine bed shear stress such as the Reynolds stress method or the turbulent kinetic energy (TKE) method, were not used to allow the comparability with both studies used to establish fine sediment cleanout depth models and the majority of studies investigating flow velocities in chalk streams.

5.4 Results

The average cleanout depth of fine sediment (<62 μm) from the gravel bed ranged from 10.9 mm (±2.7 mm) to 64.8 mm (±11.6 mm), in Run 1 and Run 9, respectively (Table 5.1). Patterns of erosion varied across the artificial chalk stream gravel bed, with certain regions experiencing greater depths of erosion compared with others (Figure 5.4). The largest variation in cleanout depths occurred in Run 9 (the highest flow velocity), with 490% increase in cleanout depths compared with Run 1. No substantial differences in cleanout depth were observed with increasing distance downstream.

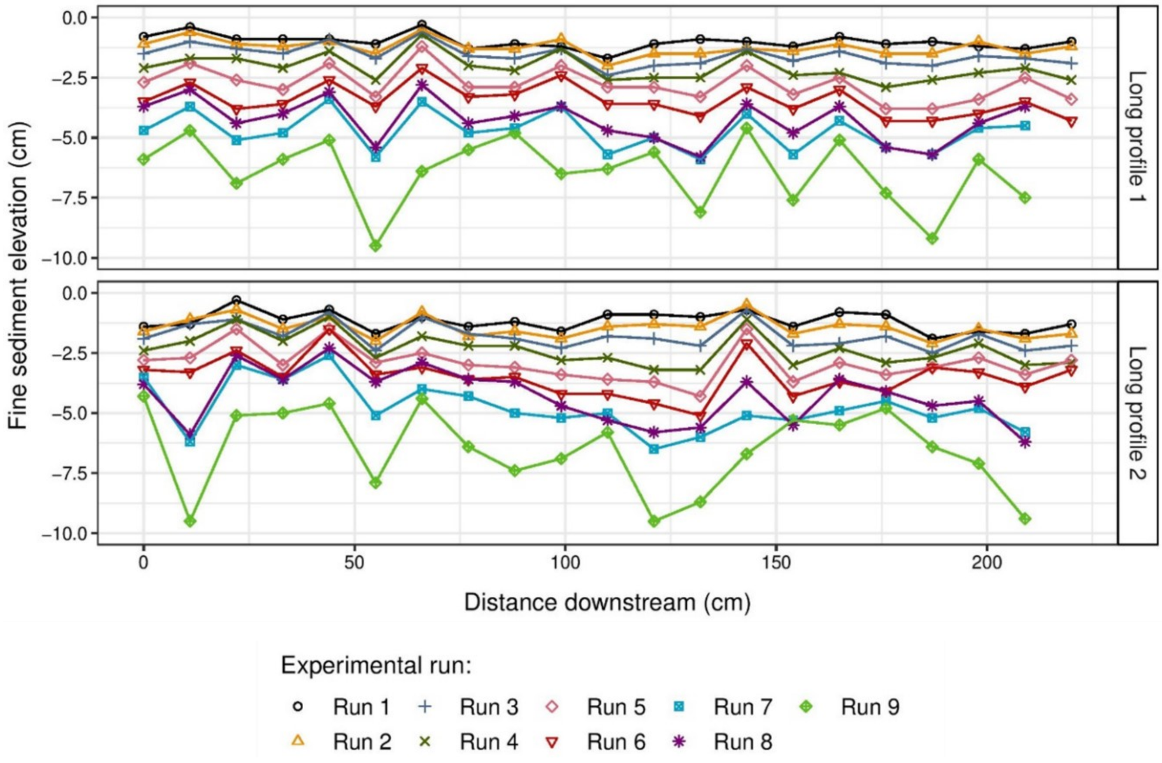


Figure 5.4: Fine sediment (<62 μm) elevations below the gravel bed surface with distance downstream post the experimental runs, for each long profile.

Increases in cleanout depths in each progressive run corresponded with increases in bed shear stresses (Figure 5.5), both in terms of the cumulative depth of fine sediment erosion in each consecutive run (Figure 5.5A) and the depth of erosion in each individual experimental run (Figure 5.5B). The deepest cleanout depths were reached in Run 9 (64.8 mm, ±15.6 mm), corresponding with the highest bed shear stress (8.08 Pa, ±0.63 Pa). This trend was not observed in Run 1, where the lowest bed shear stresses were observed to cause fine sediment erosion similar to those occurring in Run 6; however, this can likely be attributed to the flushing of fine sediment surface drapes during the initial filling of the flume. Additionally, the nature of the cleanout depth measurement method means that the initial consolidation of the gravel bed under the pressure of the water was likely to have been observed in these measurements.

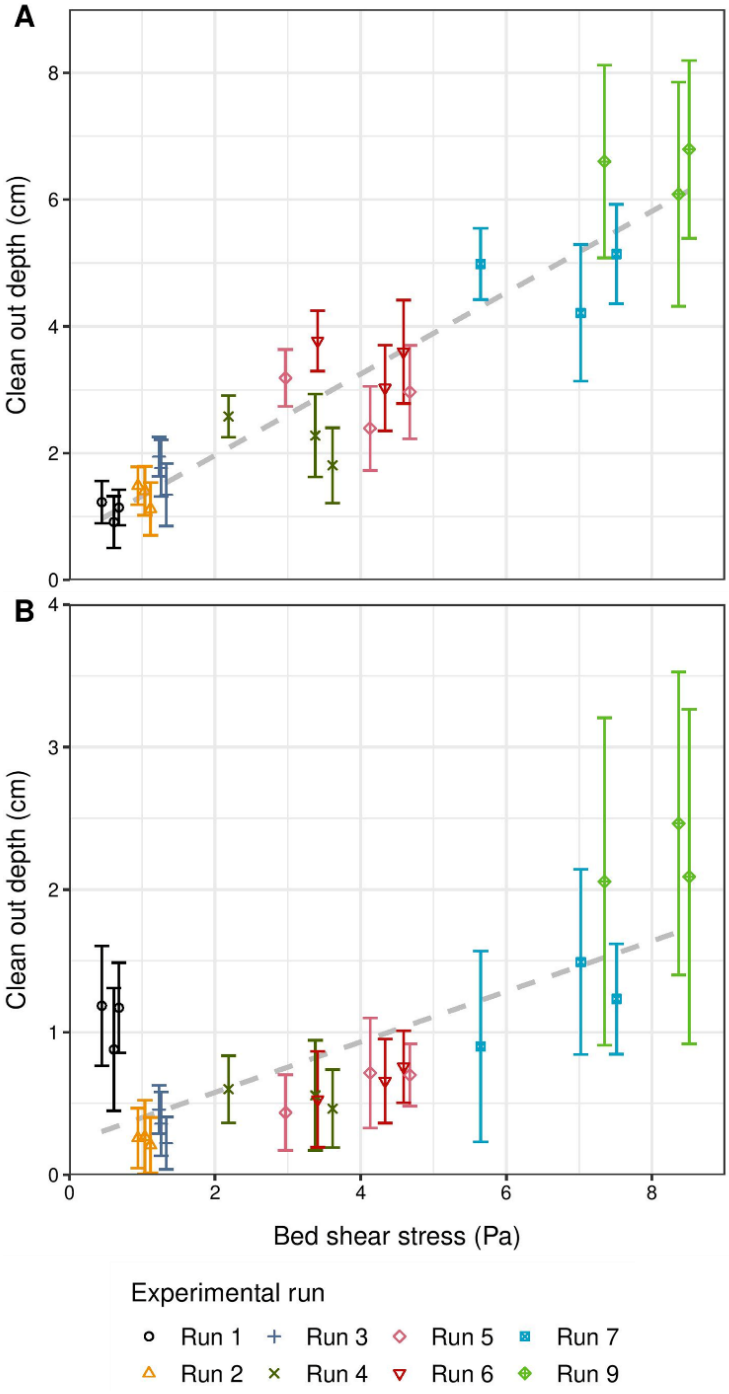


Figure 5.5: Average cleanout depth of fine sediment (<62 μm) compared with the average bed shear stress from the closest ADVP measuring location; (A) cumulative cleanout depths post each experimental run and (B) individual cleanout depths post each experimental run. Points are grouped by experimental run.

Pre-experimental runs, quantities of silt and clay particles (<62 μm) were 33.06% as a proportion of fine sediment (<1 mm) in the gravel bed, with silt particles (4 μm <*d*< 62 μm) comprising the largest fraction (32.8%). The GSD of the interstitial fine sediment was consistent throughout the gravel bed (0 – 16 cm). Post-experimental runs, the GSD of the interstitial fine sediment (<1 mm) present in the gravel bed became finer with increasing depth in the bed (Figure 5.6), with the coarsest fine sediment in the surface layer (0 – 5 cm) and the finest in the subsurface layer (5 – 16 cm). The average proportions of silt and clay particles (<62 μm) in the surface layer (0 – 5 cm) was 15.84% (±3.2%) of the total fine sediment quantity (<1 mm), a 52.8% decrease in silt and clay particles compared with the pre-experimental run gravel bed. Medium-sized sand (0.25 – 0.5 mm) was the largest fraction of interstitial fine sediment (33.6% ±3.9%), in the surface layer of the gravel bed. In contrast, in the subsurface layer (10 – 16 cm), silt and clay particles made up the largest fraction of fine sediment (<1 mm; 38.7% ±3.9%). The experimental data exhibited an average increase in silt and clay by 114% between the surface (0 – 5 cm) and subsurface layers (10 – 16 cm) of the post-experimental run gravel bed and a 15.2% increase compared with the pre-experimental run gravel bed. The average, proportions of silt and clay particles was 28.1% (±5.9%) in the middle layer (5 – 10 cm) of the gravel bed. There was a 77% increase in silt and clay between the surface and middle layer and a 37.6% increase between the middle and subsurface layer.

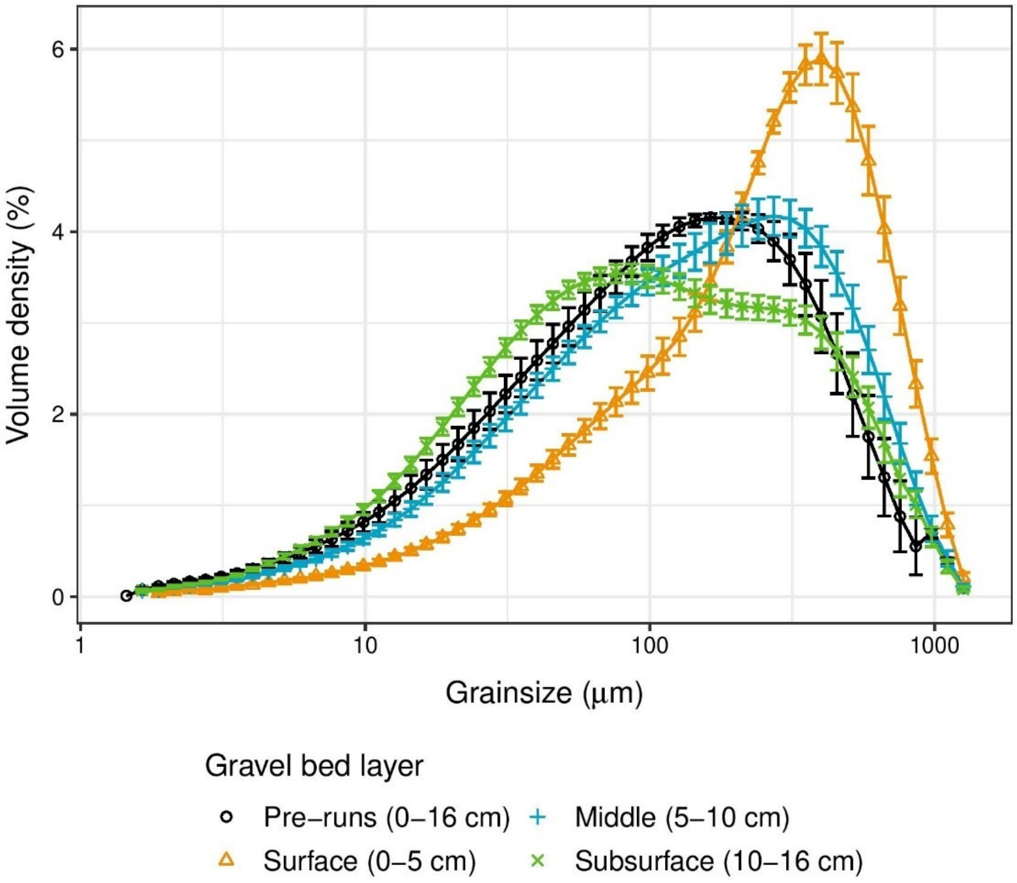


Figure 5.6: GSD of interstitial fine sediment (<1 mm) samples taken from both the gravel bed pre-experimental runs and post- the final experimental run (Run 9). Points are grouped by depth in the gravel bed.

The GSD of the suspended sediment within the water column became coarser with each progressive run, corresponding with the increase in shear velocity and bed shear stress (Figure 5.7). Here, there was an increase in the D_{50} of the suspended sediment from 36 µm to 63 µm. Silt and clay sized sediment (<62 µm) dominated the total suspended sediment volume (>64% ±8.4%) in all the experimental runs, aside from Runs 7 and 9 (54% and 45%, respectively). The largest proportion of silt and clay sized particles in the suspended sediment was observed in Run 2 (79% ±4.3 %). The largest proportion of sand sized particles transported in the water column was observed in Run 9 (57% ±6.4%); 99% of the sand consisted of predominantly very-fine and fine sand sized particles (62 µm >*d*< 250 µm). This was a 171% increase in the volume of sand sized particles within the suspended sediment compared with Run 2. The largest grain sizes transported in the water column were medium sand sized particles (250 µm >*d*< 500 µm); however, these constituted <1% of the total suspended sediment volume of any experimental run.

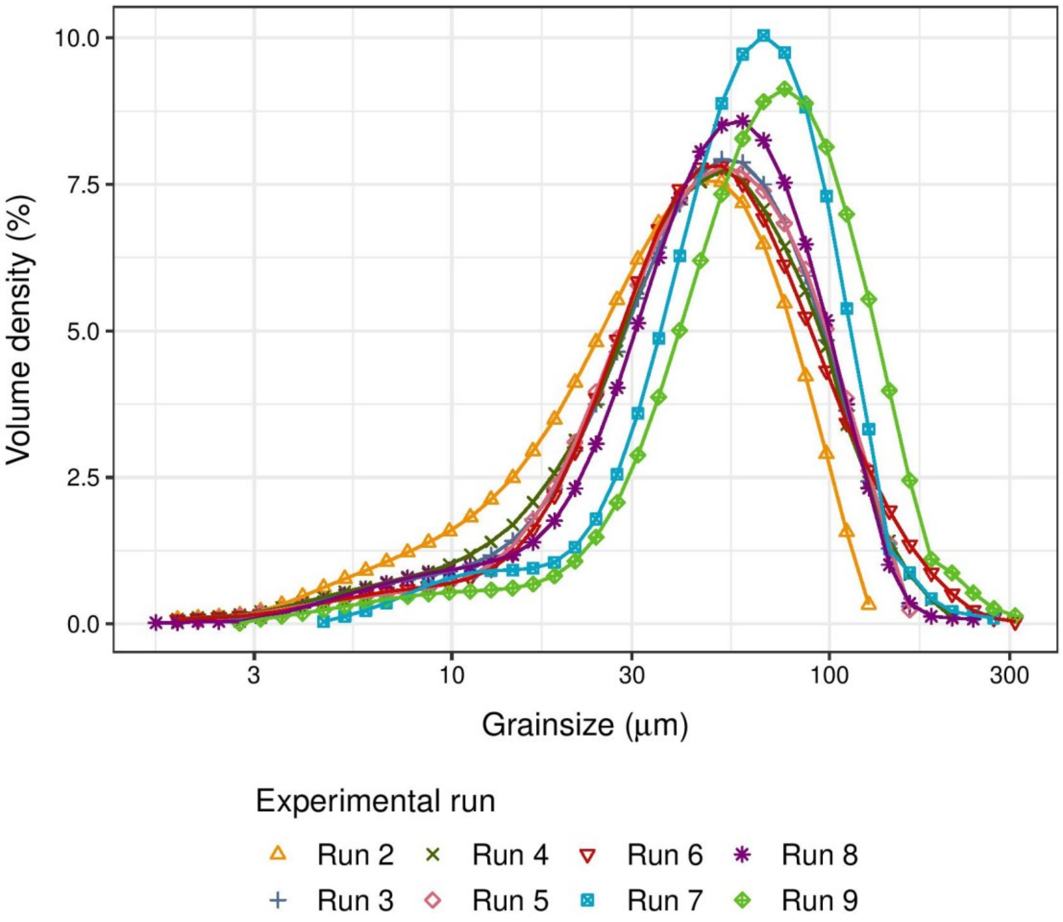


Figure 5.7: Average GSD of the suspended sediment (<1 mm in diameter) in the water column throughout the experimental runs. Points grouped by experimental run. *Run 1 – data lost.*

5.4.1 Validity of cleanout depth models

Measured cleanout depths from the present study were compared with the predicted cleanout depths from the Kuhnle et al. (2016) model. When considering the measured bed shear stress, the comparison demonstrates that the latter model does not reproduce the observed cleanout depths for either the eroded fine sediment (suspended sediment in the water column) or the bed's fine sediment grain sizes (interstitial fine sediment), overestimating the cleanout depths (Figure 5.8). The model does perform slightly better when considering the bed fine sediment grain sizes, but only for bed shear stresses >3 Pa. Values lower than this were deemed insufficient to remobilise fine sediment of this size, based on their velocity predictions. In the determination of the Kuhnle et al. (2016) model, bed shear stress values were not measured during the experiments but, instead, calculated using the relation proposed by Vanoni and Brookes (1957), as modified by Cheng (2011) (Appendix B.7). To reproduce such conditions, cleanout depths for the experimental runs in our study were also predicted using bed shear stresses calculated using this approach (Figure 5.8). However, the model does not perform any better when considering the calculated bed shear stress, still overestimating the cleanout depths. In this scenario, the calculated bed shear stresses did not exceed 3 Pa and consequently, no cleanout depths were predicted for the bed fine sediment. Nevertheless, these conditions were not observed in this study, with measured bed shear stresses >8 Pa recorded, bringing into question how representative the calculated bed shear stresses and subsequent, determination of the Kuhnle et al. (2016) model, are of the observed bed shear stresses.

Measured maximum cleanout depths from the present study were also compared with the predicted maximum cleanout depths from the Stradiotti et al. (2020) model (Figure 5.9). When considering the measured shear velocity from the present study, comparison demonstrates that the model performs relatively well when considering the bed fine sediment (D_{50} – 0.32 mm). However, it does not perform so well when considering the eroded fine sediment, overpredicting the maximum cleanout depths. Like the Kuhnle et al. (2016) model, the Stradillio et al. (2020) model was established using experiments where shear velocity was calculated and not measured directly. To reproduce these conditions, maximum cleanout depths were also predicted using shear velocity values calculated using the Kuhnle et al. (2016) approach (Appendix B.1). Despite having relatively high R^2 values, the model does not reproduce the observed maximum cleanout depths, when considering either the eroded fine sediment or the interstitial fine sediment;

with the model overpredicting for the lower calculated shear velocities and underpredicting for the higher calculated shear velocities. Subsequently, none of the predicted maximum cleanout depths using the calculated shear velocities best represented our observed maximum cleanout depths.

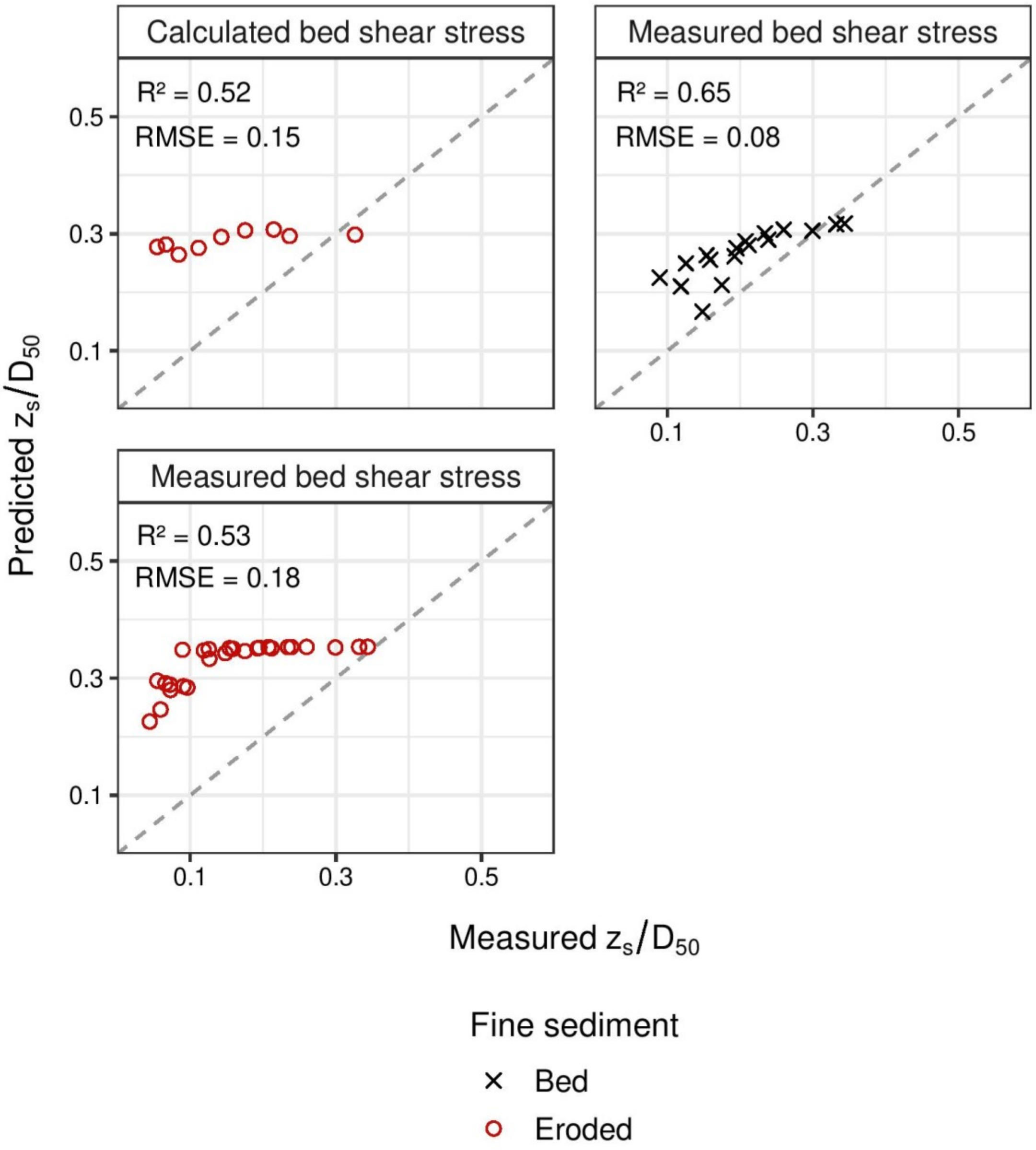


Figure 5.8: Comparison of the measured cleanout depths in this study with the cleanout depths predicted by the Kuhnle et al. (2016) model, for the eroded fine sediment (suspended sediment in the water column, D_{50} – 36 to 64 μm) in each experiment run and for the bed fine sediment (interstitial fine sediment, D_{50} – 0.32 mm) for the present study. Cleanout depth predictions have been made for the measured bed shear stress from the present study and the calculated bed shear stress from the present study, using the approach outlined in Kuhnle et al. (2016). The dashed lines represent a 1:1 relationship.

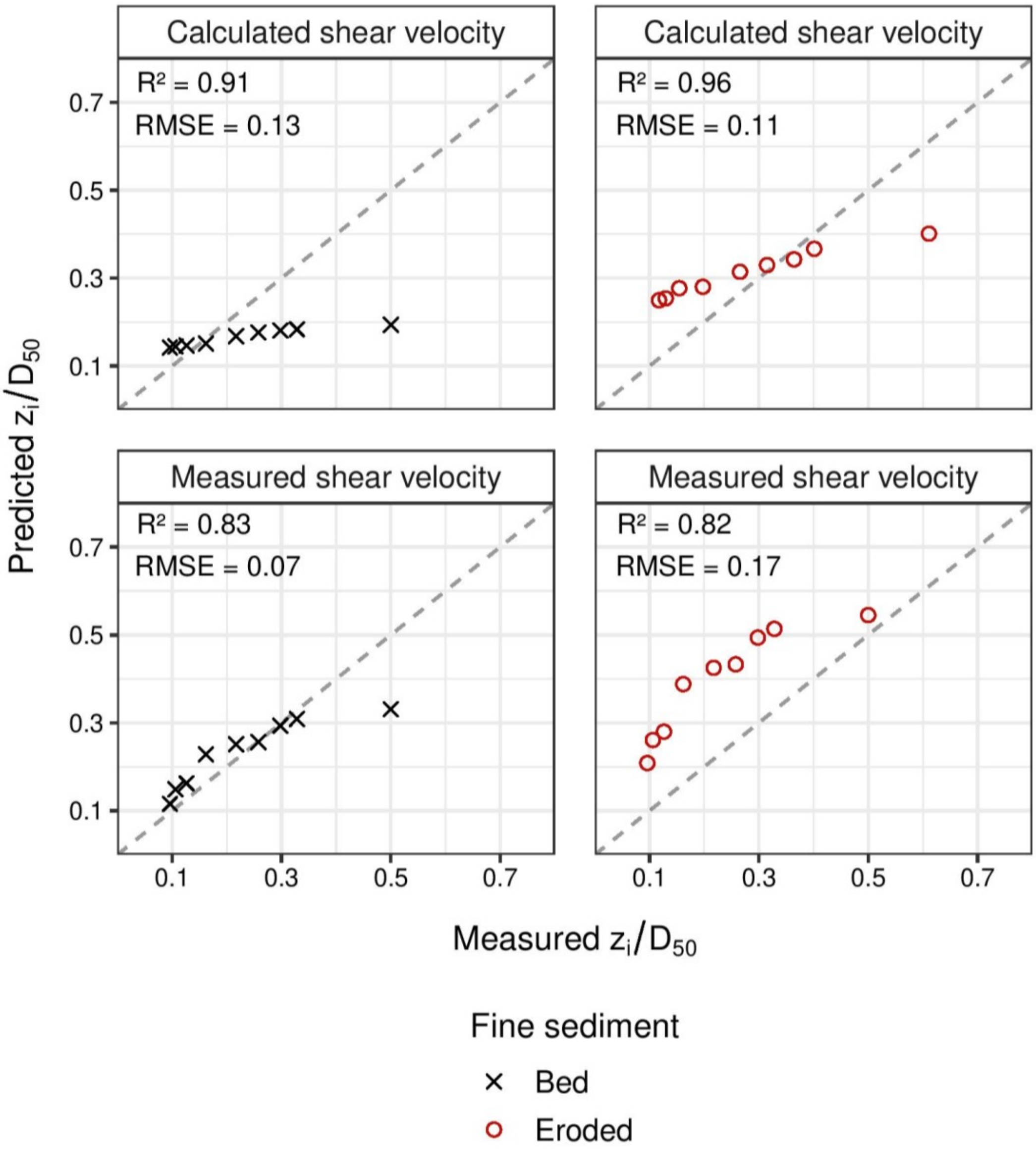


Figure 5.9: Comparison of the measured maximum cleanout depths in this study with the maximum cleanout depths predicted by the Stradiotti et al. (2016) model, for the eroded fine sediment (suspended sediment in the water column, D_{50} – 36 to 64 μm) in each experiment run and for the bed fine sediment (interstitial fine sediment, D_{50} – 0.32 mm) for the present study. Maximum cleanout depth predictions have been made for the measured bed shear stress from the present study and the calculated bed shear stress from the present study, using the approach outlined in Kuhnle et al. (2016). The dashed lines represent a 1:1 relationship.

5.5 Discussion

For the purpose of improving sediment targets and management actions required to resolve the fine sediment problem in chalk streams, the knowledge needed to establish bed mobilising flows required to remobilise accumulated fine sediment from the ecologically-sensitive surface layer (0 – 10 cm) of their gravel beds, is limited. To address this critical knowledge gap, this study investigated the influence of differing flow conditions on the remobilisation of mixed sized fine sediment (in particular, silt and clays <62 μm) from a typical chalk stream gravel bed. Increased shear velocity and near bed shear stress resulted in an increase in the depth of fine sediment erosion from the bed, with the greatest cleanout depths (6.5 cm ±1.6 cm) observed under flow conditions with a mean bed shear stress of 8.2 Pa. Cleanout depths were influenced by two processes within the bed. Firstly, flushing of fines from the bed, evident by the substantial decrease (52%) in fine sediment (<62 μm) quantities in the surface layer (0 – 5 cm) of the post-experimental runs bed compared with the quantities in the bed for the pre-experimental runs. Second, hydraulic winnowing of fines within the bed, evident by the slight increase (17%) in fine sediment (<62 μm) quantities in the subsurface layer (10 – 16 cm) of the post-experimental bed compared with the quantities in the pre-experimental bed (Figure 5.7). The observed variations in the cleanout depths during runs can likely be attributed to the influence of protrusions of the gravel bed (Grams and Wilcock, 2007; Trevisson and Eiff, 2022), which create localised areas of scour and deposition. Gravel protrusions can reduce the stress acting on fine sediment by exerting drag on the flow and can also influence fine sediment entrainment by introducing local velocity and pressure excursions in their wakes (Grams and Wilcock, 2007; Schmeeckle et al., 2007).

The observations of this study support the findings of previous experimental studies (e.g., Kuhnle et al., 2016; Stradiotti et al., 2020), which showed that the depth of fine sediment erosion in a gravel bed was proportional to the shear velocity at the bed. However, despite comparable shear stresses and subsequent cleanout depths being observed, the fine sediment eroded in the present study was considerably smaller in GSD (average D_{50} – 0.042 mm across the runs) compared with those eroded in the Kuhnle et al. (2016) study (D_{50} – 0.2 mm), indicating that other factors are influencing the depth of fine sediment erosion and/or the corresponding critical thresholds of erosion. One such factor is the influence of cohesion. Cohesive particles (silts and clays <62 μm), experience interparticle attractive forces which shear stresses must exceed in order to break the electrochemical bonds (Wu et al., 2018). Multiple studies have demonstrated that the addition of clay to sand deposits increased their resistance to erosion (e.g., Panagiotopoulos et al., 1997; Lick et al., 2004; Grabowski et al., 2010). The addition of clay has been demonstrated to fill the voids between the sands, smoothing the bed surface, and making it more resistant to erosion. The influence of cohesive particles is a potential explanation for the minimal erosion of sand from the chalk stream gravel bed in the present study.

Differences in the GSDs of the experimental gravel beds will have also influenced the erosion depths of fine sediment. For example, the gravel beds used in both the Kuhnle et al. (2016) and Stradiotti et al. (2020) experiments were stylised, with large gravel particles resulting in a substantial difference between the gravel framework GSD and the interstitial fine sediment GSD. Bed porosity is influenced by the size and heterogeneity of the sediment: gravel beds, for example, with uniform particles sizes, will have greater porosity than a bed with a wide range of particle sizes (Wooster et al., 2008; Núñez-González et al., 2016). Subsequently, the experimental gravel beds used by Kuhnle et al. (2016) and Stradiotti et al. (2020) will likely have a higher porosity compared with the gravel bed in the present study. A higher porosity in the gravel bed increases intra-gravel flows and movement of fine sediment (Wooster et al., 2008; Núñez-González et al., 2016), which has the potential to increase fine sediment remobilisation and cleanout depths, resulting in the deeper cleanout depths for coarser fine sediment. Importantly, the gravel bed conditions in previous studies do not represent those occurring in the natural environment, where gravel beds consist of a full range of grain sizes and often show little size difference between the smallest bed particles and largest fine sediment (e.g., Carling and Reader, 1982; Carling, 1983; Lambert and Walling, 1988; Milan et al., 2000) due to the presence of cohesive fine sediment >62 μm (e.g., Owens et al., 1999; Walling and Amos, 1999; Collins et al., 2005; Collins and Walling, 2007).

5.5.1 Implications for modelling

Physically-based modelling requires robust quantification of erosion parameters such as the critical shear stress for erosion. The present study provides new knowledge on the critical shear stresses required to remobilise fine sediment from the ecologically-sensitive surface layer (0 – 10 cm) of a typical chalk stream gravel bed and used this data to test the suitability of currently established models in predicting cleanout depths for fine sediment in chalk stream gravel beds.

Comparison between the observed and predicted cleanout depths using the Kuhnle et al. (2016) and Stradiotti et al. (2020) models, under both types of bed shear stress and shear velocity scenarios, demonstrated that these established models overpredict the cleanout depths in chalk stream gravel beds in 86% and 50% of cases, respectively. These outcomes can potentially be attributed to a number of factors that were not considered in these models and/or differences between experimental conditions. For example, the Kuhnle et al. (2016) model was calibrated using cleanout depths of sand-sized particles: this influences several aspects within the model. The model uses a fall velocity equation that is based on sand-sized particles (proposed by Cheng, 2009, Appendix B.8), which assumes that if a particle diameter decreases, so does the fall velocity of the particle: the critical bed shear stress required to mobilise the particle is thus lower. Similarly, the Stradiotti et al. (2020) model was calibrated using the cleanout depths of sand-sized particles; however, their model does not consider the fall velocity of the fine sediment. Instead, the model considers the geometric characteristics of the fine sediment (D_{50}). Subsequently, these models neglect the potential influence of cohesion in particles of <62 μm (silts and clays), which influences the critical thresholds for particle remobilisation. Cohesive sediment has been shown to react with gravel beds, stabilising them and entrapping fine sediment, increasing the critical shear stress required for erosion of the sequestered fine sediment (Glasbergen et al., 2014; Stone et al., 2021). This indicates that particle size alone is, therefore, not a sufficient indicator of the critical threshold for particle motion.

In addition, the overly stylised GSDs of the gravel beds used to determine both the Kuhnle et al. (2015) and Stradiotti et al. (2020) models influence a number of factors that control fine sediment erosion from the bed. An estimation of the porosity of the gravel beds used in both the Kuhnle et al. (2016) experiments and the chalk stream gravel bed in the present study, 0.37 and 0.16 respectively (estimated using the approach proposed by Wooster et al. (2008), Appendix B.9), demonstrate a substantial difference. The lower porosity in the gravel bed within the present study compared with the experimental beds used to establish the existing models, could explain why those models overpredict cleanout depths, as porosity was not considered in either instance. Furthermore, the Kuhnle et al. (2016) model assumes that fine sediment erosion is limited to the surface layer of the gravel bed based on the calculated CPDG, which the model assumes is directly related to the roughness geometry thickness (RGT) of the gravel bed. However, observed cleanout depths in this study herein suggest that this is not necessarily the case, with erosion occurring deeper than the measured RGT; approximately 7.1 cm compared with maximum cleanout depths exceeding 9 cm. This indicates that the RGT does not represent the surface layer of the experimental gravel bed and/or that fine sediment erosion under these conditions is not limited to the surface layer of the bed. Since the Stradiotti et al. (2020) model does not use the CPDG of the bed to predict the cleanout depth, their predictions are not limited to the bed surface. Instead, the Stradiotti et al. (2020) model is valid until shear velocity values for the threshold of the bed framework sediment movement are exceeded. As no bed movement was observed in the present study, the Stradiotti et al. (2020) predictions are still valid.

5.5.2 Implications for management/sediment targets

Both sediment source and the transport capacity of a system influence the propensity of chalk streams to accumulate fine sediment within their gravel beds. Therefore, management that addresses both these factors is critical if the problem of excessive fine sediment in chalk streams is to be addressed efficiently and effectively. The majority of chalk stream gravels beds already have elevated quantities of fine sediment present within their frameworks; for example, 89% of 90 analysed chalk stream gravel beds were found to be over-saturated with fines (Section 4.5.3). Reducing fine sediment inputs will not impact the fine sediment already accumulated in chalk stream gravel beds because chalk stream bed material is not naturally remobilised, even during bank-full events. Subsequently, improvements in the propensity of chalk stream systems to remobilise fine sediment from the gravel beds must be a focus of targeted management. Reach-scale restoration can create localised areas of increased flow, that would increase the shear velocities and bed shear stress. For example, the installation of woody material and management of instream macrophytes can create localised regions of higher velocity, promoting increased bed shear stress and remobilisation of fine sediment (Gurnell et al., 2006; Heppell et al., 2009; Osei et al., 2015; Parker et al., 2017). In addition, the removal of channel obstructions such as weirs can increase localised flow velocity (Lenders et al., 2016). Furthermore, these types of restoration and management techniques are more self-sustaining than previous approaches such as manual gravel washing (Pander et al., 2015) as they restore hydrological and sedimentological processes instead of focusing on moving fine sediment from one place to another. Furthermore, these approaches create heterogenous flow patterns within systems, which in turn, create a heterogeneous habitat within the gravel bed. For example, instream macrophytes create regions of lower flow within their stands, promoting highly localised fine sediment deposits (Gurnell et al., 2006; Heppell et al., 2009; Osei et al., 2015), which are critical for certain life-cycle stages of some chalk stream species, e.g., the ammocoete stage of European river lamprey (*L. fluviatilis* L.) (Silva et al., 2015). The present study gives new insight into the critical shear velocities and bed shear stresses required to mobilise fine sediment, notably fine sediment (<62 μm), from a typical chalk stream gravel bed and provides much-needed and robust data. These data can direct the extent to which these management and restoration techniques need to be applied to chalk streams to deal with the fine sediment problem and improve the ecological status of chalk stream gravel beds.

There is potential for additional study to develop further the data provided here. For example, no movement of the bed sediment was observed under the investigated bed shear stress scenarios, indicating that the chalk stream gravel frameworks could withstand higher shear stress conditions before the movement of bed particles is initiated. However, the inclusion of cohesive sediment can stabilise the bed and therefore increase the critical threshold of movement. Future research should identify the maximum shear stresses chalk stream gravel beds can experience before initiation of bed particle movement, aiming to help direct the limits of future fine sediment management without damaging or removing the crucial chalk stream gravel frameworks. In addition, having compiled data on cleanout depths for a gravel bed with a typical chalk stream GSD, further work could be carried out to establish if any regional differences in chalk stream gravels bed GSDs have an influence on the bed shear stresses required to mobilise fine sediment from their gravel beds. For example, the gravel beds of Norfolk chalk stream systems are known to have higher quantities of sand-sized fine sediment particles than Hampshire/Dorset chalk streams. Therefore, the remobilisation of such fine sediment may occur differently i.e., larger fine sediment grain sizes are remobilised but with less influence of cohesive sediment. In addition, the impact of climate change on flow conditions and fine sediment remobilisation in chalk streams should be considered in potential sediment targets and management. Groundwater recharge of chalk aquifers is expected to occur over shorter periods due to climate change, a consequence of longer, hotter, and drier summers, where evapotranspiration is greater, and shorter, and more intense winter rainfall periods, which end earlier in the year (Allen and Crane, 2019; Stubbington et al., 2022). Shorter periods of groundwater recharge will reduce the groundwater-dominated flows in chalk streams, further decreasing their bed mobilising propensity and increasing fine sediment deposition. These impacts could be further compounded by increased fine sediment inputs, as intense rainfall on exposed dry soils has the potential to increase sediment-laden runoff. Chalk stream systems will therefore most likely lack resilience to climate change and exacerbate erosion and sediment delivery to channel systems.

5.6 Conclusions

Cleanout depths of interstitial fine sediment were measured in a series of progressive flume experiments using fine sediment and a gravel bed with GSDs typical of UK chalk streams, and under differing flow conditions. Increased bed shear stresses corresponded with increased fine sediment cleanout depths, with the greatest cleanout depths of 6.5 cm (±1.6 cm) observed under flow conditions with an average bed shear stress of 8.2 Pa. Cleanout depths varied across the artificial gravel bed, reflecting likely patterns of scour and deposition created by areas of increased and decreased shear stress around protruding bed particles. Two processes of fine sediment movement were identified as important to remobilising fine sediment from the surface layer of gravel beds: flushing and hydraulic winnowing. These were evident by the patterns in the fine sediment quantities within the gravel beds post-experimental runs. The validity of previously established models used to predict fine sediment cleanout depths from immobile gravel beds was tested using the data from these experiments. Comparison between observed and predicted cleanout depths demonstrated that for most of the scenarios considered, these models did not reproduce the observed cleanout depths, but often overpredicting them. This outcome can be attributed to assumptions in the existing models and failure to consider characteristics of naturally occurring gravel beds, importantly those in chalk streams. Subsequently, the application of such models is not suitable to direct mitigation of excessive deposited fine sediment in chalk streams. The established bed shear stress values required for the cleanout of fine sediment from the ecologically-sensitive surface layer (0 – 10 cm) of chalk streams from our experiments can be used to help direct revised sediment targets, management, and restoration activities. Further improvements to these measurements could be made by considering the regional differences in the sedimentological characteristics of chalk streams and by establishing the maximum bed shear stresses a chalk stream gravel bed could experience without the motion of the gravel framework which provides essential benthic refuges.

Chapter 6 Synthesis, outlook, and conclusions

This chapter brings together the key outcomes of the core chapters (Chapter 3, Chapter 4, Chapter 5) of this thesis. A synthesis of the novel research, in relation to the overall aims of this thesis (Section 2.1), how the results of this thesis could impact future fine sediment targets, management and restoration techniques and the scope for future work, is presented.

Fine sediment (inorganic and organic particles <2 mm in diameter) is a natural component of freshwater ecosystems and plays a critical role in the geomorphology, ecology, and hydrology of river systems. However, in recent decades, river systems globally have experienced increasing inputs of fine sediment compared with pre-industrial levels (Walling and Fang, 2003; Owens et al., 2005; Foster et al., 2011; Collins and Zhang, 2016). These increases have been attributed to anthropogenic activities both within river catchments and instream, altering fine sediment inputs into river networks and their response to elevated fine sediment loads (Wohl, 2015; Grabowski and Gurnell, 2016; Evans, 2017). Elevated quantities of fine sediment have been identified as one of the main contributors leading to the degradation of freshwater at global scale (Malmqvist and Rundle, 2002; Dodds et al., 2013; Zhang et al., 2014; Wilkes et al., 2019), and with substantial detrimental impacts on freshwater organisms (e.g., Wood and Armitage, 1997; Bilotta and Brazier, 2008; Kemp et al., 2011; Jones et al., 2012a; 2012b; 2017). These ecological impacts can occur via two processes; firstly, elevated suspended sediment in the water column, resulting in increased turbidity and direct damage to biota and secondly, elevated deposition and accumulation of fine sediment within gravel beds, resulting in the blocking of interstitial pore space and consequent reductions in intra-gravel permeability and porosity (Veličković, 2005; Sear and DeVries, 2008; Grischek and Bartak, 2016; Fetzer et al., 2017; Wharton et al., 2017).

Chalk streams naturally present with relatively low suspended sediment yields, compared with other UK fluvial systems (Heywood and Walling, 2003; Walling et al., 2007; Cooper et al., 2008). This characteristic is due to limited sediment available for transport, a consequence of their groundwater dominated flow regimes and subsequent low bed mobilising flows (Sear et al., 1999; Walling and Amos, 1999). Chalk stream channel forms reflect this characteristic in having high width to depth ratios, limited connectivity between the land surface and river networks, and low rates of bank erosion (Sear et al., 1999; Heywood and Walling, 2003). Despite this, the gravel beds of chalk streams regularly exhibit higher quantities of accumulated fine sediment compared with other UK gravel bed systems (Acornley and Sear, 1999; Milan et al., 2000; Sear and DeVries, 2008). This has been attributed to the natural hydrological regime of chalk streams, most notably their low bed mobilising flows, and numerous anthropogenic activities. Elevated fine sediment inputs into chalk streams have resulted from increases in catchment soil erosion, runoff, and field to river connectivity, both of which are consequences of the shift from low-intensity farming to high intensity autumn-sown cereal production and amalgamation of small fields to larger fields in chalk stream catchment (Boardman, 2003; Boardman, 2013; Grabowski and Gurnell, 2016; Evans, 2017; Boardman et al., 2019). The low bed mobilising flows characteristic of chalk streams have been further compounded by over-abstraction of the chalk aquifers (reducing groundwater inputs), and the construction of channel modifications (over-widening, weirs, and hatches etc.), all of which have homogenised flow conditions and increased residence times in chalk streams, promoting fine sediment deposition and accumulation within their gravel beds (Figure 3.2) (Bickerton et al., 1993; Petts et al., 1999; Wohl, 2015).

The clean, coarse gravel beds of chalk streams provide the ideal habitat for numerous nationally and internationally important freshwater organisms (see Table 3.1). However, numerous chalk stream gravel bed species have been demonstrated to be intolerant of elevated accumulated fine sediment quantities, especially during critical life-cycles stages, resulting in substantial ecological degradation. For example, the survival and recruitment of incubating salmonid eggs has been reported to be substantially and negatively affected by elevated fine sediment accumulation in gravel beds, due to reductions in both dissolved oxygen exchange and removal of metabolic waste (Greig et al., 2005a; 2005b; 2007; Pattison et al., 2014; Sear et al., 2016; 2017). The limited ability of chalk streams to remobilise accumulated fine sediment from their gravel beds, coupled with these organisms' relative immobility during critical life-cycles stages, has created the high potential for long-lasting and lethal/sub-lethal impacts that needs to be addressed.

6.1 An alternative approach to sediment targets and management in chalk streams

There currently exists only one sediment target for freshwater systems in the UK, a suspended solids limit of 100 mg L^{-1} in wastewater discharges (Environment Agency, 2018a). However, whether this is still considered or enforced is unclear, as multiple government guidance reports on water targets state that there are currently no in-river sediment standards in the UK (Environment Agency, 2021; Defra, 2022). Previous sediment targets, include the annual mean suspended sediment target of 25 mg L^{-1} in the repealed EU FFD (78/659/EC) (Collins and Anthony, 2008). However, the reinstatement or improvement of sediment targets like those previously implemented within the UK would not provide a suitable basis for effective and successful management in chalk streams. Section 3.4.1 concludes that the use of oversimplified targets such as the use of single, blanket annual mean suspended sediment target across multiple systems, is inappropriate, given the high spatial and temporal variability in sediment budgets. This is particularly so, when considering chalk streams, which regularly have substantially lower suspended sediment yields than in other UK river systems (Walling et al., 2007; Bilotta et al., 2012). Even if improvements to suspended sediment targets were to be implemented, i.e., targets that consider the differences in the hydrological and sedimentological regimes between systems, they would still not be a suitable approach. This is because suspended sediment targets currently assume that there is a direct and linear concentration-ecological dose-response to fine sediment, with increasing fine sediment loads assumed to result in increasing detrimental ecological impacts. However, this is not necessary the case. Adverse impacts can occur at lower fine sediment concentrations due to the interplay of additional factors such as timing of delivery, grain sizes, sediment source and species life-cycle stage of affected biota (Greig et al., 2007; Sear et al., 2016; Bašić et al., 2019). Nevertheless, it was concluded (Section 3.4.1) that the consideration of these factors in alternative sediment targets would still be insufficient in chalk streams, as the use of suspended sediment targets alone does not explicitly link the fine sediment problem of elevated fine sediment accumulation with its causation, which is the main cause of ecological degradation in chalk streams.

To address the failure to link the accumulation of fine sediment in chalk stream gravel beds and its causation within revised sediment targets and management, an alternative system-based sediment budget approach was proposed (Section 3.5.1), whereby all the critical factors controlling fine sediment accumulation in chalk stream gravel beds are considered explicitly, and not the suspended sediment load in isolation. These factors are split into four distinct overarching mechanisms (Figure 3.3): (A) inputs of fine sediment into a channel system from the surrounding catchment and/or channel margins (Section 3.5.1.1); (B) transport of fine sediment in the water column as suspended load or bedload (Section 3.5.1.2); (C) infiltration of fine sediment into gravel beds (Section 3.5.1.3), and; (D) exfiltration of fine sediment from gravel beds (Section 3.5.1.4). To established the most suitable revised management and restoration approaches to reduce fine sediment accumulation in chalk streams, the factors both instream and within chalk catchments that influence the overarching mechanisms of the proposed sediment budget were discussed further in Section 3.5.1. The proposed sediment budget framework highlights that in low stream power systems such as chalk streams, it is the low bed mobilising flows characteristic of such systems that controls the accumulation of fine sediment within their gravel bed frameworks. It was established that this factor heavily influences two of the overarching mechanisms within the sediment budget: the infiltration of fine sediment into the gravel bed and the exfiltration of fine sediment from the gravel bed (Section 3.6). The sediment budget framework proposed in Section 3.5.1 highlights that sediment targets and the resultant management and restoration techniques in chalk streams need to focus on their low bed mobilising flows and, consequently, the dominant mechanisms controlling the accumulated fine sediment within their gravel beds. In this instance it was recommended to focus on the remobilisation of fine sediment from the gravel beds to prioritise sediment targets and revise management and restoration techniques, in order to reduce the elevated quantities of accumulated fine sediment.

6.2 Characterisation of the sedimentology of chalk stream gravel beds

Chapter 3 highlighted the need for revised sediment targets and management in chalk streams to focus on the mechanisms that control the accumulation of fine sediment in their gravel beds and strongly influence sediment budgets. However, for this to be determined, improvements in the knowledge surrounding fine sediment accumulation in chalk streams was required. Work presented in Chapter 4 took the first necessary steps in this process, by characterising the sedimentological characteristics of chalk stream gravel beds and, importantly, the quantities and distribution of fine sediment within their gravel bed frameworks. Using existing sediment metrics that link the processes of bed structuring, fine sediment infiltration and bed saturation, freeze-core data from 90 gravel bed sites across 11 UK chalk streams (Figure 4.2) were analysed (Section 4.5). Average quantities of fine sediment (<2 mm) in the gravel beds were 25% (±12.8%) of the total bed weight (Table 4.3), and importantly, 89% of the investigated gravel bed frameworks were over-saturated with fine sediment (Section 4.5.3; Figure 4.5). The determination of the saturation state of the investigated chalk stream gravels was based on the model proposed by Wooster et al. (2008), whereby the quantities of fine sediment have exceeded the maximum amount of fine sediment that can infiltrate the gravel bed framework before it no longer considered *framework-supported*. Elevated quantities of accumulated fine sediment in chalk streams gravel beds have been well-established to cause substantial detrimental ecological impacts in (e.g., Greig et al., 2007; Rosewarne et al., 2014; Sear et al., 2016; Everall et al., 2018). Investigations into the distribution of fine sediment intolerant chalk stream species (e.g., Louhi et al., 2008; Stubbington et al., 2015; Bunting et al., 2021), have indicated that the surface 10 cm of chalk stream gravel beds are the most ecologically sensitive (Section 4.6.2). Of the investigated chalk stream gravel beds in Section 4.4.1 (Figure 4.2), >50% of the surface layers (0 – 10 cm) exceeded fine sediment quantities or thresholds identified as unsuitable for salmonid spawning and recruitment (Greig et al., 2005a; Heywood and Walling, 2007). Although, the use of species-specific thresholds may not be entirely appropriate in assessing the overall ecological suitability of chalk stream gravel beds, the use of sensitive species has the potential to act as effective indicator species and the limited knowledge on other non-salmonid species renders it necessary. Consequently, it was established that revised fine sediment targets and management should focus on the ecologically- sensitive surface layer (0 – 10 cm) of chalk stream gravel beds.

Comparison (Section 4.5.5) between the determined chalk stream gravel bed sedimentological characteristics and the characteristics of experiments used to determine models describing fine sediment infiltration and accumulation in immobile gravel beds (Figure 4.7), highlighted that vertical variations of fine sediment quantities in chalk streams observe the opposite trend to those in published laboratory-based experiments (Table 4.1). This indicated that these current models are not representative of the natural characteristics and processes occurring in chalk stream gravel beds. It was concluded (Section 4.6.1) that this is a consequence of these experimental designs failing to represent the natural sedimentological characteristics of chalk stream gravel beds. For example, the majority of experimental gravel beds had smaller GSDs (D_{50} <10 mm; e.g., Gibson et al. (2010); Dudill et al. (2017)), than in a typical chalk stream gravel bed (D_{50} – 19.6 mm; Table 4.3) and both the experimental fine sediment and gravel beds had sorting coefficients of moderately well-sorted samples (e.g., little variation in the grain sizes present) compared with chalk steams that have sorting coefficients of poorly sorted samples (e.g., high variation in grain sizes present). It was, therefore, concluded (Section 4.6.1) that the considered experimental data were not reflective of the natural conditions observed in chalk streams and this brings into question the representativeness of existing models derived from experimental data. As such, future experiments and models describing fine sediment-gravel bed interactions must be representative of chalk stream sedimentological characteristics if robust and scientifically based sediment targets and management are to be established.

Although there were overall trends in the sedimentary characterises of chalk stream gravel beds identified in Section 4.5, differences in the fine sediment quantities and characteristics were identified between systems. The quantities of fine sediment in the gravel beds were shown to relate with the system's stream power (Section 4.6.3; Figure 4.8), supporting the conclusions of previous studies (Sear and DeVries, 2008; Naden et al., 2016; McKenzie et al., 2022). For instance, the River Test had one of the lowest average stream powers of the investigated chalk streams (Table 4.2) and thus lacked the shear velocities required to remobilise fine sediment contributing to the highest fine sediment quantities (Table 4.3). Additionally, the minimal differences in fine sediment quantities between the River Test's surface and subsurface layers (Table 4.4) was further evidence of low stream power; i.e., stream power in the River Test is likely to be insufficient to create near bed turbulence sufficient to even remobilise fine sediment from the surface layer of the gravel beds. However, stream power was also not found to explain all the observed variations in fine sediment quantities across the investigated chalk stream gravel beds; sediment source (e.g., land-use and local geology) was also identified as a potential control (Section 4.6.3). Higher proportions of arable land in the River Itchen catchment compared with other South-western chalk streams potentially explained the higher proportion of fine sediment present (particularly silts and clays); agricultural land has been identified as one of the main contributors to fine sediment inputs in lowland river systems (e.g., Collins and Walling, 2007b, Collins et al., 2009; Zhang et al., 2014). Similarly, the higher proportions of sand-sized fine sediment in the Norfolk systems' gravel beds (Figure 4.3) were attributed to easily erodible sandy soils in their catchments, a consequence of ice marginal processes during in previous glacial periods (Section 4.6.3). The findings of Chapter 4 further reinforce the suggestions of the sediment budget framework in Section 3.5.1, whereby, fine sediment targets and instream management and restoration techniques in chalk streams need to focus on the low bed mobilising flows controlling the quantities and rates of fine sediment accumulation, in particular the remobilisation of fine sediment from the ecologically-sensitive surface layer (0 – 10 cm) of the gravel beds.

6.3 Targets for fine sediment remobilisation from chalk stream gravel beds

Chapter 4 highlighted that both the stream power of a system and sediment-sources, influence a chalk streams propensity to accumulate fine sediment, and that both are key considerations in revised targets and management of the fine sediment issue in chalk streams. Nevertheless, given that chalk streams already have elevated proportions of fine sediment (89% are over-saturated with fines, Figure 4.5) and that bed material is not naturally mobilised during bankfull events, reducing fine sediment inputs alone will have little impact on the fine sediment already accumulated. Revised sediment targets and management should thus focus on the improvement of bed mobilising flows to remobilise fine sediment from the ecologically-sensitive surface layer of their gravel beds. However, knowledge surrounding this issue was found to be limited in existing research literature.

Chapter 5 addressed this research need. An experimental flume study was carried out to establish the depths of fine sediment (<2 mm, in particularly silts and clays <62 µm) remobilisation from the ecologically-sensitive surface layer (0 – 10 cm) of a typical chalk stream gravel bed under differing flows conditions (Section 5.3.1). It was highlighted (Sections 4.5.5 and 4.6.1) that current models representing the interactions of fine sediment and immobile gravel beds are not representative of the natural characteristics occurring in river systems, most notably chalk streams. To achieve suitable representativeness of the natural sedimentological characteristics of typical chalk stream gravel beds in the flume study of Chapter 5, the GSD of the artificial gravel bed was determined using the data from freeze-core analysis presented in Section 4.5 (D_{50} of a typical chalk stream gravel bed framework of 19.7 mm (Table 4.3), compared with the D_{50} of the artificial gravel bed in the flume of 19.8 mm (Figure 5.2)). In addition, the GSD of the artificial chalk stream bed included a full range of grain sizes and thus had a representative sorting coefficient. This better represented the conditions naturally occurring in chalk streams. Suitable representation of the natural sedimentological characteristics of gravel beds has been lacking in previous flume experiments investigating fine sediment-gravel bed interactions. The new experiments undertaken as part of this research (Section 5.4) showed that increases in bed shear stresses and shear velocities resulted in an increase in the cleanout depths of fine sediment, with the greatest cleanout depths (6.5 cm ±1.6 cm) observed under flows conditions with a shear velocity of 0.0915 m s^{-1} and a bed shear stress of 8.2 Pa (Figure 5.5). The patterns of fine sediment quantities and cleanout depths post-experimental runs was attributed to two processes of sediment movement: hydraulic winnowing and flushing from the bed. In addition, protrusions of the gravel bed created areas of scour and deposition (Grams and Wilcock, 2007; Trevisson and Eiff, 2022), which were the likely cause of the observed local variations in fine sediment cleanout depths (Figure 5.4). Although similar cleanout depths were observed in the current experiments under comparable flow conditions to those in previous studies (e.g., Kuhnle et al., 2016; Stradiotti et al., 2020), there was a substantial difference in the grain sizes of the eroded fine sediment. Eroded fine sediment in the flume study described herein (Figure 5.7) had an average D_{50} of 0.042 mm compared with an eroded fine sediment D_{50} of 0.2 mm in the study reported by Kuhnle et al. (2016).

The data collected in Chapter 5 were used to test the validity of previously established models (Kuhnle et al., 2016; Stradiotti et al., 2020) in predicting the cleanout depths of fine sediment from gravel beds (Section 5.4.1). Comparison between the observed and predicted cleanout depths demonstrated that the Kuhnle et al. (2016) and Stradiotti et al. (2020) models performed poorly, often overpredicting the fine sediment cleanout depths (Figure 5.8 and Figure 5.9). The flume study (Section 5.5.1) concluded that this was attributable to several assumptions and a failure to consider the natural sedimentological characteristics of chalk stream gravel beds. This included the influence of cohesion in the fine sediment, which was not considered in the establishment of either model, as both were based on the remobilisation of sand-sized particles that do not experience cohesion. In the present study a full range of particles sizes were considered, including silts and clays (Figure 5.2), which do experience cohesion (Droppo, 2001; 2004; Woodward and Walling, 2007). Cohesive sediment has been shown to react with gravel beds, stabilising them and entrapping fine sediment, increasing the critical shear stress required for fine sediment remobilisation (Glasbergen et al., 2014; Stone et al., 2021). In addition, the gravel beds used to calibrate the Kuhnle et al. (2016) and Stradiotti et al. (2020) models had overly stylised GSDs, with low sorting coefficients and which would influence a number of factors controlling fine sediment remobilisation from the bed (e.g., porosity). Higher porosities within gravel beds, increase intra-gravel flows and movement of fine sediment (Wooster et al., 2008; Núñez-González, 2016) and, as such, the exclusion of gravel bed porosity in the current models could have affected their performance. These findings further support those of Section 4.6.1, in that the application of such models is not appropriate to directly underpin the management of excessive accumulated fine sediment in chalk streams. The results of Chapter 5 give some of the first scientifically robust data (e.g., the use of an artificial bed with a GSD representative of a typical chalk stream gravel bed) which can direct the revised and more targeted management of fine sediment in chalk stream gravel beds. The determination of the required bed shear stresses/shear velocities needed in chalk streams to remobilise excessive fine sediment from their ecologically-sensitive gravel bed surface layer (0 – 10 cm), can help to direct the extent and magnitude of management needed in chalk streams.

6.4 Implications for revising chalk stream fine sediment targets and management

The findings presented in Chapter 5 provide one of the first robust and scientifically based targets for a key mechanism (the exfiltration of fine sediment from the gravel bed) controlling fine sediment accumulation in gravel beds, in the chalk stream sediment budget framework proposed in Section 3.5.1. The data provided herein can inform revised sediment targets and management needed in chalk streams to restore their bed mobilising flows to the levels required to remobilise elevated quantities of fine sediment from the ecologically-sensitive surface layer (0 – 10 cm). Given the high sensitivity of chalk stream biota to elevated fine sediment quantities and the substantial proportion of chalk stream gravel beds that are over-saturated with fine sediment, such data to direct revised targets and management is needed if the ecological status of chalk streams are to be improved.

Despite this, bed shear stresses and shear velocities are not easily measured in the field, requiring extensive and costly monitoring of river systems. Additionally, there is a lack of data from chalk streams concerning these factors, likely a consequence of the problems in measuring them. As a result, it is difficult to establish whether the established bed shear stresses and shear velocities required to remobilise fine sediment from the ecologically-sensitive surface layer (0 – 10 cm) of chalk stream gravel beds are being reached in systems, or whether they are even attainable under current hydro-geomorphological conditions. One approach to make the shear velocities more appropriate and comparable with factors that can be readily measured in river systems, is to calculate the depth averaged velocities needed to achieve the required shear velocities. Subsequently, depth averaged velocities ($\overline{U}$) needed to remobilise fine sediment from the surface layer (0 – 10 cm) of chalk stream gravel beds (using the maximum shear velocity value from the flume experiments in Section 5.3.1), were predicted for each of the investigated chalk stream sites in Section 4.4.1, using the law of the wall Equation (6.1) (Carling, 1984):

$$\bar{U} = (u^{*})\frac{1}{k}\ln\left(\frac{h}{z_0}\right) \tag{6.1}$$

where k is the von Karman constant (0.4), h is the height above the bed (in this instance 0.4 x b, the water depth), u^{*} is the shear velocity where deepest fine sediment cleanout depths were observed (0.0915 m s^{-1}) and z_0 is the bed roughness, calculated using Equation (6.2):

$$z_0 = 0.65D_{50} \tag{6.2}$$

where, D_{50} is the median grain size of each of the investigated chalk stream gravel beds. The depth averaged velocity predictions were then compared with depth averaged velocities that have been previously measured in chalk streams, under several different channel conditions (Figure 6.1). An overview of the eight original studies used in Figure 6.1, including details on the sampling design and technique, is given in Appendix C.1. The decision was taken to only consider studies that provided depth averaged velocities (or where it was possible to calculate depth average velocities based on the available data such as velocity profiles), so that the data was comparable to the predicted flow velocities. Although, some of the original studies included information on the spatial distribution of velocity measurements within channels, overall, this information was lacking and for most cases only cross-sectional averages or one-off examples had been represented. As such, the decision was taken not to consider the influence of spatial distribution within the channel when comparing the predicted velocities with depth averaged velocities recorded in chalk streams.

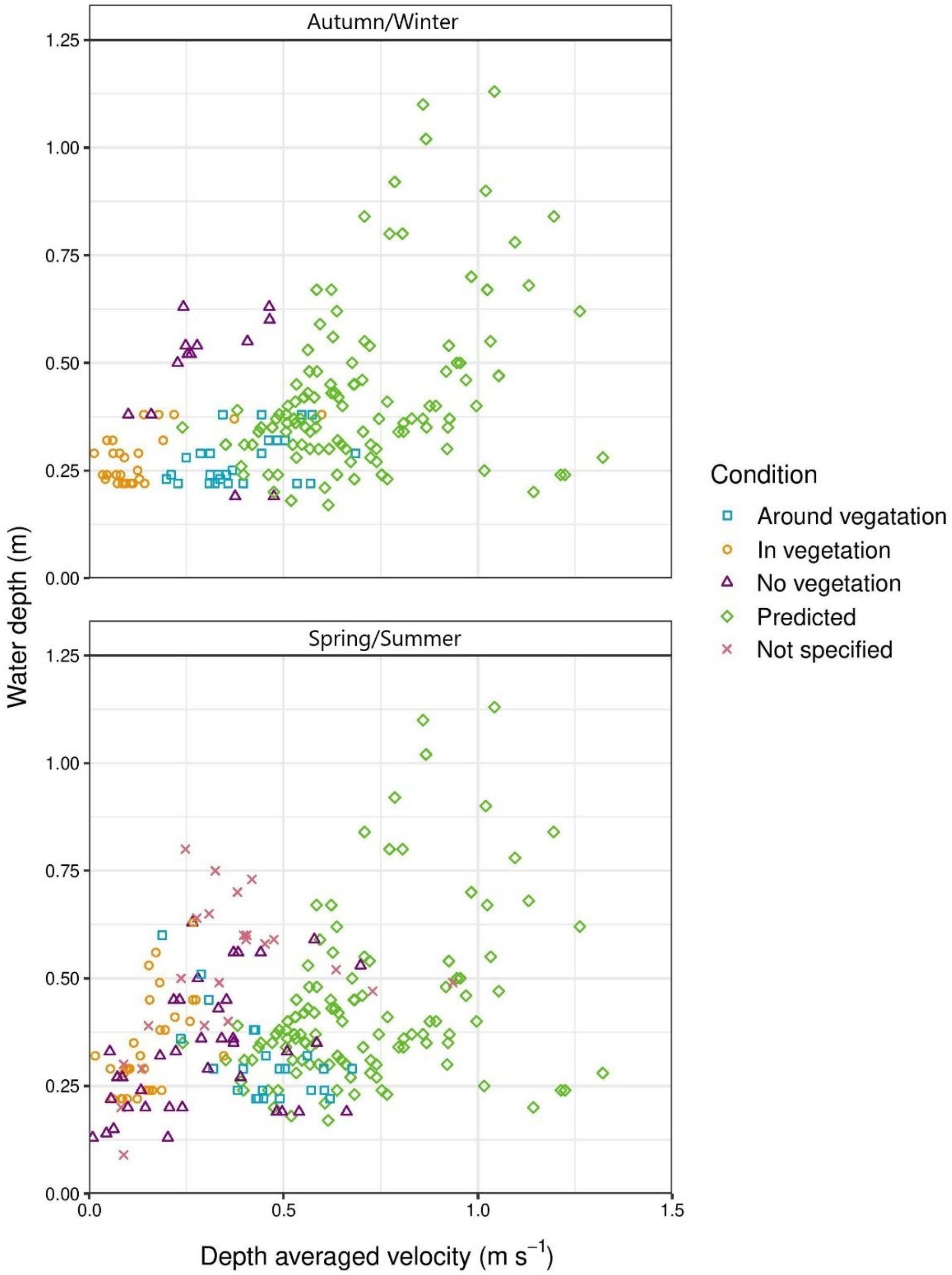


Figure 6.1: Predicted depth averaged velocities needed to achieve the established shear velocity value (Section 5.4; 0.0915 m s^{-1}), required to remobilise fine sediment from the surface layer (0 – 10 cm) of the investigated chalk stream gravel beds (Section 4.4.1), compared with the depth averaged velocities previously recorded in chalk streams under various channel conditions, as depicted in the figure legend (Marshall and Westlake, 1990; Green, 2005; Gurnell et al., 2006; Wharton et al., 2006; Warren et al., 2009; Grabowski, 2011; Old et al., 2014; Mullen, 2016). Depth average velocities are split by autumn/winter flows (September, October, November, December, January, February) and spring/summer flows (March, April, May, June, July, August).

The comparison between the predicted and observed depth averaged velocities in chalk streams highlight that for the most part, chalk streams are not achieving the needed depth averaged velocities required to remobilise fine sediment from the surface layer (0 – 10 cm) of their gravel beds. This supports findings of this study (Section 4.6.3), where >50% of the investigated chalk stream gravel bed surface layers (0 – 10 cm) had fine sediment quantities exceeding those established to cause substantial ecological degradation. Although there is some cross-over between the predicted and observed velocities, this was only for the highest observed velocities and the lowest predicted velocities. Importantly, most of the observed velocities in chalk streams achieving values similar to the predicted velocities were measured in flows around patches of aquatic macrophytes, which have been well-established to alter flow conditions (e.g., Cotton et al., 2006; Gurnell et al., 2006; Wharton et al., 2006; Gurnell and Bertoldi, 2022). However, there is quite a high likelihood that the measured chalk stream velocities in Figure 6.1 do not include extreme high flow/flood events, due to logistical and safety constraints associated with field sampling. These high flow events could potentially reach the determined shear velocity thresholds required to remobilise fine sediment from gravel beds, but their occurrence is expected to be minimal due to the dampening effects of groundwater dominated inputs. It should also be noted, that although the shear velocity value established in Section 5.4 and used here to predict the required depth averaged velocities, was sufficient to remobilise fine sediment from up to 10 cm within the gravel bed, the average cleanout depth was 6.5 cm across the experimental gravel bed (Section 5.4). This was attributed to the influence of framework particle protrusions on shear stresses, which are known to cause localised areas of scour and deposition (Grams and Wilcock, 2007; Trevisson and Eiff, 2022). Subsequently, these predicted depth averaged velocities should potentially be seen as a minimum requirement for chalk stream depth averaged velocities, to further ensure that fine sediment is continually remobilised from the ecologically-sensitive surface layer (0 – 10 cm) of their gravel beds.

Flow velocities of a river system are directly related to the systems stream power, which is a function of the system's discharge, width, and slope (Petit et al., 2005). To increase stream power and thus flow velocities, at least one of these factors must be altered. Increases in channel slopes can increase the flow velocities within the channel. However, the low slope values characteristic of chalk streams cannot be altered without substantial costly and heavily invasive restoration; such alterations are unlikely to achieve the increase in depth averaged velocities required and are therefore unsuitable. Similarly, increases to chalk stream discharges are not readily achievable due to their predominantly groundwater-dominated flows, although further reductions in discharge can be mitigated by enforcing restrictions on abstraction from the chalk aquifers (Soley et al., 2012). Subsequently, only the channel widths can be efficiently altered with practical restoration and management techniques. Alternations in a river's channel width have been demonstrated to affect flow velocities and the transport capacity of the system, with flow velocities (including the depth averaged velocity) and sediment mobilisation demonstrated as increasing with decreasing channel width (Wang et al., 2016; Chartrand et al., 2018; Cook et al., 2020).

Despite this, restorations to reduce the overall channel width would likely involve extensive and expensive approaches. For example, Section 4.6.4. highlighted that for chalk streams to achieve similar stream powers to those observed in gravel bed systems where fine sediment quantities are consistently low (Figure 4.8), would require width reductions to <1 m. In the lower reaches of chalk streams channel widths often exceed 20 m and thus, substantial reductions in the channel width would be required to achieve the predicted velocities. Such restoration attempts would likely require the construction of multiple anabranching channels, in order to reduce channel widths and increase bed mobilising flows without losing the flow capacities of the system and thereby minimising the risk of increased flooding. Although this form of restoration has been proven successful, especially in the US (e.g., Powers et al., 2019; Hinshaw et al., 2022; Medel et al., 2022), it requires extensive areas of land. Due to the need for agricultural land, substantial urban areas and complications arising from multiple landowners, the extensive areas of land needed for such large-scale river restoration projects in chalk stream catchments is unlikely to exist, especially in the lower reaches. Consequently, practical, and achievable management and restoration activities must be considered instead. These include instream approaches that have the same effect as reducing the channel width but on a localised reach-scale, creating a patchy stream velocity environment within the channels. Such management and restoration techniques include for example, the installation of large wood, the management of instream aquatic macrophytes and removal of channel obstruction such as weirs. In chalk stream that have experienced extensive dredging, the re-instatement of gravel beds is also critical. Chalk streams do not naturally possess the bed flows or sufficient supply of gravel require to replenish the gravel beds through natural processes (Sear et al., 2006). In these situations, more drastic and costly restoration approaches including the re-instatement of gravel beds are potentially required, as the introduction of large wood and/or aquatic macrophyte management would not sufficiently increase the flow velocities required to mobilise gravel sized sediment.

6.4.1 Potential management and restoration activities

Large wood jams naturally occur within river systems, but have been routinely removed from channels for centuries, particularly in lowland systems, in an attempt to improve navigation and drainage (Roni et al., 2015; Wohl, 2015; Cashman et al., 2019). However, in recent years, there has been increasing recognition of the advantages of more structurally complex large wood installations in river systems, including in chalk streams, and their influence on flow velocities and sediment regimes (Osei et al., 2015; Parker et al., 2017; Harvey et al., 2018; Cashman et al., 2019; Grabowski et al., 2019). This includes the introduction of strong spatial variations in the localised flow velocities and shear stresses and therefore, the sediment transport capacity of the flow. Specifically, concentrated flows in the areas adjacent to the large wood increase the flow velocities, reducing rates of fine sediment deposition and potentially increasing fine sediment remobilisation from the bed. Conversely, slower flows within the large wood decrease flow velocities, increasing fine sediment deposition and reducing fine sediment remobilisation from the bed (Parker et al., 2017; Harvey et al., 2018; Cashman et al., 2021). Flows can also occur underneath the large wood, if the water depth is sufficient, creating localised high flow velocities and shear stresses, increasing bed scour and remobilisation of fine sediment (Grabowski et al., 2019). Similarly, instream aquatic macrophytes in lowland systems, including chalk streams, have been well-established to cause strong spatial variations in flow velocities, which subsequently modify sediment dynamics at reach scale (Gurnell et al., 2006; Cotton et al., 2006; Heppell et al., 2009; Liffen et al., 2013; Gurnell and Bertoldi, 2022). In particular, hydraulic resistance within the aquatic macrophyte patches reduces flow velocities, reducing fine sediment remobilisation from the bed and increasing sediment deposition; concentrated flows in areas between aquatic macrophyte patches increase the flow velocities, increasing bed scour and remobilisation of fine sediment from the bed and reducing fine sediment deposition (Gurnell et al., 2006; Cotton et al., 2006; Heppell et al., 2009; Grabowski and Gurnell, 2015). Most cases where observed velocities in chalk streams are achieving those required to remobilise fine sediment from the surface layer of gravel beds (Figure 6.1) have occurred in the flows around patches of aquatic macrophytes. Consequently, large wood installations and aquatic macrophytes act as a sediment traps, storing substantial quantities of fine sediment, creating cleaner framework gravel alongside them (Heppell et al., 2009; Grabowski and Gurnell, 2015; Osei et al., 2015; Cashman et al., 2021). In addition, fine sediment accumulation within large wood installations and in emergent aquatic macrophytes has been demonstrated to narrow the width of chalk stream channels, further inducing localised increases in flow velocity and increasing the potential for remobilisation of fine sediment from the gravel bed framework (Grabowski and Gurnell, 2015; Harvey et al., 2018; Gurnell and Bertoldi, 2022).

Instream structures, such as weirs, impact the hydraulic and sedimentological processes within river systems. Weirs specifically are known to increase water depth upstream of the structure, creating an area of low flow velocities, reducing stream power and thereby, increasing fine sediment deposition and reducing remobilisation of fine sediment from the gravel beds. Hydraulic conditions are more turbulent downstream of weirs due to the formation a hydraulic jump, increasing flow velocities and the remobilisation of fine sediment from the gravel beds. However, this can also result in excessive scour of the bed, mobilising the gravel bed framework particles (Csiki and Rhoads, 2010; Anderson et al., 2015; Poeppl et al., 2015). These impacts can also increase the width of channels both upstream (due to the backwater pool) and downstream (due to excessive bank erosion), over-widening of channels can further reduce flow velocities, increasing fine sediment deposition and reducing fine sediment remobilisation (Fencl et al., 2015). A recent study found that there are >60,000 artificial barriers, including weirs, in the UK river systems and that <3.3% of the total river length in the UK is unfragmented by these structures (Jones et al., 2019). Most of these weirs were constructed pre-1990s, primarily to provide hydraulic head for mills and fishing and to maintain adequate channel depth for navigation (Rickard et al., 2003; Bennett et al., 2014; Brown et al., 2018). Regardless, the vast majority of these instream structures no longer serve their original purpose(s) (Foster et al., 2022), yet continue to influence hydrological and sediment processes in river systems. The removal of these instream structures could restore hydrological and sedimentological regimes in river systems such as chalk streams, as well restoring the longitudinal connectivity in systems.

A number of issues have been raised with these forms of management and restoration: issues include the longevity of large wood in systems, the effects excessive aquatic macrophyte growth, and the potential negative impacts of the release of stored fine sediment post-weir removal. Regardless, the suggested benefits of such management in improving the heterogeneity of flow velocities, fine sediment storage and subsequent ecological improvements, have the potential to clearly outweigh these issues in the long term. Furthermore, these forms of management and restoration are more advantageous to chalk streams compared with previous restoration techniques to remove fine sediment from gravel beds such as manual gravel washing (e.g., Pander et al., 2015), as they restore hydrological and sedimentological processes in chalk streams, instead of just addressing the consequence. In addition, the management and restoration activities as proposed have further ecological benefits for chalk streams. For example, the formation of localised fine sediment deposits in both aquatic macrophyte stands and large wood jams creates habitats critical for certain life-cycle stages of various chalk stream species, e.g., ammocoete stage of European river lamprey (*L. fluviatilis* L.) (Silva et al., 2015) and burrowing mayflies (*Ephemeroptera*) (Jacobus et al., 2019). It is evident (see Figure 6.1) that the management of aquatic macrophytes in some cases alters flow velocities to those required to achieve fine sediment remobilisation from the ecological-sensitive surface layer of chalk stream gravel beds. However, further research is needed to determine whether the installation of large wood, continued management of instream aquatic macrophytes, and removal of instream structures (i.e., weirs) can alter flow velocities in chalk streams to those that are sufficient to remobilise fine sediment from the ecologically-sensitive surface layer (0 – 10 cm) of their gravel beds. Additionally, further evidence is required of the potential disbenefits in chalk streams (at least in the short-term) of these proposed management and restoration techniques and consequently, any longitudinal strategies that need to be implemented to ensure the continued movement of remobilised fine sediment downstream.

6.5 Limitations and future work

The literature review carried out (Section 3.3.3.2) highlighted a bias towards salmonid species in terms of research of the ecological impacts of elevated fine sediment quantities in chalk stream gravel beds. Consequently, ecologically detrimental thresholds for accumulated fine sediment in UK chalk stream gravel beds have not been determined other than for salmonid species. As a result of this, the establishment of the ecological suitability of chalk stream gravel beds (Section 4.6.2) was based solely on the reported fine sediment thresholds for salmonid recruitment and survival. Future research on the detrimental impacts of accumulated fine sediment quantities on other lithophilic fish and other aquatic biota (i.e., macroinvertebrates, aquatic macrophytes) has the potential to alter thresholds for ecological suitability on a broader and more meaningful basis. As such, the determined ecological suitability of the current state of chalk stream gravel beds may have to be reassessed.

Analysis of secondary freeze-core data (Section 4.5) gave a good representation of the chalk stream gravel bed sedimentological characteristics. However, there is the potential for better representation. This could be achieved by further research into the regions/chalk streams that have not been previously investigated, such as chalk streams in the Thames, Sussex and/or Kent regions. This could also highlight if there are any further regional variations in the sedimentological characteristics of chalk streams gravel beds in addition to those already determined (Section 4.5). Comparison of freeze-core data from multiple published and unpublished studies (Section 4.5.5), highlighted a lack of standardisation in both the analysis and presentation of data. This included but was not limited to; not following the Wentworth particle size categories, incomplete GSDs or only focusing on grain size the individual study deemed important and varying depth used to establish layers within the gravel beds (e.g., Milan, 1994; Mitchell, 2015). These issues hindered the ability for meaningful comparison of sedimentological characteristics between different chalk stream systems and meant that not all the data could be included in the analyses in this study. For instance, the lack of a reported full GSD for all the bed layers in the Norfolk systems, meant the infiltration mechanisms could not be determined (Section 4.5.4). Consequently, a more standardised approach should be taken in future freeze-core studies, including sticking to the Wentworth particle size grading, the inclusion of a full GSDs of both the gravel bed (framework) particles and fine sediment (matrix) particles, and splitting the freeze-cores into comparable layers (i.e., 10 cm layers). Such standardisation in freeze-core reporting would allow for more efficient comparison and consistent determinations of the sedimentary characteristics of chalk stream gravel beds.

The GSDs of the artificial gravel bed and fine sediment used in the flume experiments (Chapter 5) were representative of a typical chalk stream gravel bed; analysis of data from a wide range of chalk streams (Section 4.6.3) identified regional differences in the GSDs. Further research could be undertaken to establish what potential influence the regional gravel bed GSDs could have on the flow conditions required to remobilised fine sediment from the surface layer of the gravel bed. During the flume experiments (Chapter 5) the maximum flow conditions the flume could produce were reached. However, no movement of the bed particles were observed under these conditions. Subsequently, future work should be carried out to determine the maximum bed stress stresses a typical chalk stream gravel bed can experience before the initiation of bed particle movement. This can be done to help determine the maximum extent and magnitude of revised sediment management and restoration that should be carried out in chalk streams, without damaging or remobilising the crucial and naturally irreplaceable gravel bed frameworks. Furthermore, any potential trade-off risks of remobilised fine sediment in the absence of any longitudinal strategy to prevent the remobilised fine sediment being redeposited downstream need to be investigated.

6.6 Concluding remarks

The overall aim of this thesis was to establish new system-specific and ecologically-relevant targets for the dominant mechanism (from the proposed chalk stream sediment budget) controlling elevated quantities of accumulated fine sediment in chalk stream gravel beds. Taken together, the chapters of this thesis meet this objective by providing a new target for the shear velocities required to remobilise fine sediment from the ecologically-sensitive surface layer (0 – 10 cm) of a typical chalk stream gravel bed. A new conceptual framework was developed for a chalk stream sediment budget, which incorporated the four overarching mechanisms controlling fine sediment accumulation in chalk streams. Stream power, most notably the characteristic low bed mobilising flows, was identified as the most critical factor in chalk streams in controlling the elevated quantities of fine sediment within their gravel beds. Thus, the exfiltration of fine sediment from gravel beds was highlighted as the dominant mechanism of the sediment budget in order to prioritise revised sediment targets, management, and restoration activities. As a key control on these mechanisms, the sedimentological characteristics of chalk stream gravel beds were then determined, based on previously published and unpublished freeze-core data from chalk streams across the UK. This highlighted that the majority of chalk stream gravel beds (89%) were over-saturated with fine sediment and that >50% of the ecologically-critical surface layers (0 – 10 cm) had fine sediment quantities exceeding reported thresholds for ecological degradation. The determined chalk stream gravel bed sedimentological data were then used to evaluate the representativeness of existing models describing fine sediment-gravel bed interactions for chalk streams. It was established that the experimental designs used to determine these current models were not representative of the natural conditions in chalk streams due to overly stylised gravel bed and atypical fine sediment characteristics. As such, these models are unsuitable for the determination of evidence to support revised sediment management in chalk streams. A new target for flow velocities required to remobilise fine sediment (in particular, silts and clays <62 μm) from the ecologically-sensitive surface layer (0 – 10 cm) of a typical chalk stream gravel bed was established using new flume experiments, carried out under differing flow conditions. To ensure the experimental design more closely represented the natural conditions of chalk stream gravel beds, the GSDs of both the gravel bed and fine sediment were taken from the determined sedimentological characteristics. The established flow velocities were then compared with measured flow velocities from chalk streams and indicated that for the most part, the flow velocities required to remobilise fine sediment are not currently being achieved in chalk streams. Instream management and restoration techniques that could be implemented in chalk streams in attempt to achieve these flow velocities were discussed. The established flow velocities herein are some of the first scientifically robust targets which can direct potential restoration and management activities, aimed at reducing quantities of accumulated fine sediment within chalk stream gravel beds. In the absence of any sediment targets, the multiple and varied impacts of elevated fine sediment quantities in chalk streams are largely unquantified and are not being addressed. Until bespoke chalk stream sediment targets are recognised and adopted in policy and process, actions to restore these systems to more favourable conditions cannot be efficiently or effectively implemented or measured.

Appendix A Supplementary material for Chapter 4

A.1 Original freeze-core studies

Overview of the original freeze-core studies used to compile the GSDs used in the chalk stream gravel bed database, detailing the purpose of the original study, sampling techniques and localised spatial distribution of samples.

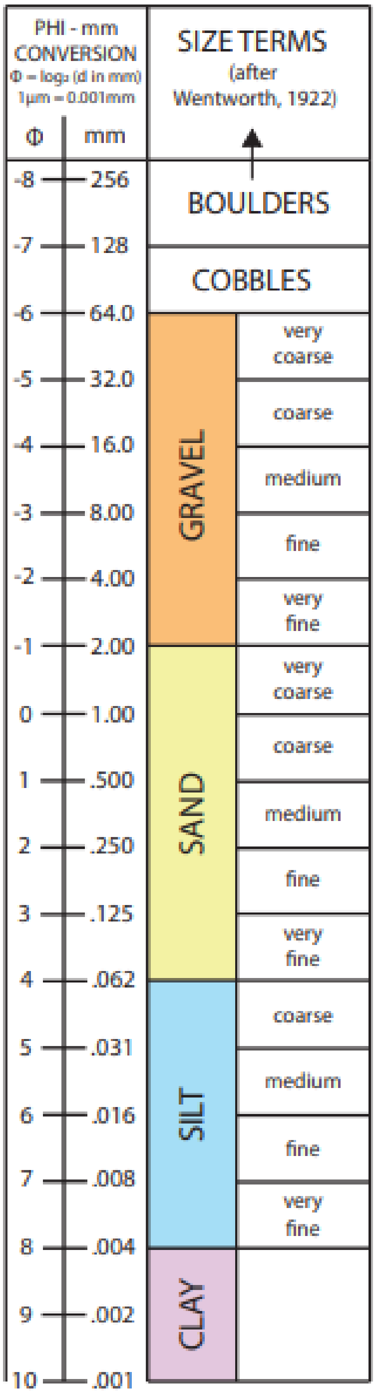
Study	*Rivers*	*Reason for study*	*Freeze-core technique*	*Spatial distribution of freeze-cores*
Barron (1982)	Test	Investigation on gravel bed sedimentological characteristics and quantities of fine sediment.	Freeze-core technique was not detailed in the original report.	Sampling location and replication details were not detailed in the original report.
Carling (1983)	Piddle, Bere Stream, Tadnoll Brook	Investigation on grain size composition, packing and siltation of void space and organic content on salmonid spawning gravel beds.	Followed the technique outlined in Carling and Reader (1981). Dried and dry sieved.	25 cores. The data presented in the report was an average of the cores for each river due to minimal variation between samples. Exact location of the cores in the channel was not detailed in the
Beaumont (1993)	Avon, Upper Avon, Nadder, Wylye, Piddle, Frome	Investigation of gravel bed composition and fine sediment quantities and distribution, with reference to salmonid spawning areas.	Corer size – 25 mm in diameter. Freezing was not carried out within a confined volume and no weights pooled were detailed. Combination of wet and dry sieving.	Three replication cores were taken at each of the sampling sites. Exact locations of the cores within the river channels were not detailed in the original report.
Milan (1994)	Babingley, Wissey	Thesis investigation into sediment quality characteristics of Brown trout spawning gravel beds in lowland chalk streams.	Carbon dioxide freeze-coring. Corer size – 25 mm in diameter. Freezing was not carried out within a confined volume. Cores were approximately 30 cm in length and between 3 and 8 kg in weight.	A minimum of five replication cores were taken at each of the sampling sites, exact location of these cores in the channel was not detailed in the original report. The data presented in the original report was an average of the cores.

A.1 continued:

Acornley (1999)	Test	Investigation into the influence of water temperature in gravel beds on salmonid spawning.	Liquid nitrogen freeze-core technique modified from Carling (1981).	Sampling location and replication details were not detailed in the original report.
Riley et al. (1999)	Itchen	To assess the long-term efficiency of jet washing on fine sediment quantities in modified and unmodified gravel beds. To improve their suitability for salmonid	Corer size – 50 mm in diameter and 1300 mm in length. Freezing was not carried out within a confined volume and no weights pooled were detailed. Wet and dry-sieved.	Five cores were taken at equal intervals across the river channel at each sampling site. The data presented in the original report is an average of these five cores.
Greig et al. (2005)	Test	Investigation into the impacts of fine sediment accumulation on oxygen concentrations and survival of incubating salmonid eggs.	Freeze-core technique was not detailed in the original report.	Sampling location and replication details were not detailed in the original report.
Bateman (2012)	Itchen	Thesis investigating the impacts of organic and inorganic fine sediment accumulation in salmonid spawning gravel beds.	Liquid nitrogen freeze-core technique. Freezing was not carried out within a confined volume and no weights pooled were detailed. Wet and dry-sieved.	Two replication cores were taken at each of the sampling sites, exact location of these cores in the channel was not detailed in the original report.
Mitchell (2015)	Stiffkey	Thesis investigating the effectiveness of gravel bed restoration on Brown trout spawning success.	Corer size – 50 mm in diameter and 1300 mm in length. Freezing was not carried out within a confined volume and no weights pooled were detailed. Wet and dry-sieved.	Three replication cores were taken at each of the sampling sites, taken from the upstream, downstream, and mid-point of the sampling site.

A.2 Wentworth scale

Wentworth scale of particle sizes (Bunte, 2001), separating particles in size classes increasing by a factor of two (e.g., 2 – 4 mm, 4 – 8 mm, 8 – 16 mm). These size classes are grouped into six major particle-size categories: boulders, cobbles, gravel, sand, silt, and clay (adapted from (Wentworth, 1922)).



A.3 Geometric method of moments

Geometric method of moments (adapted from (Blott and Pye, 2001)).

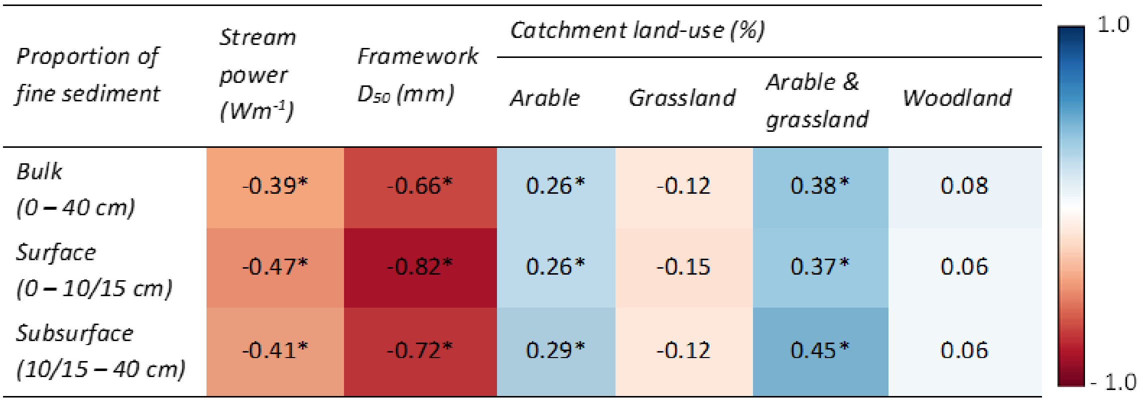
Mean	*Sorting (standard deviation)*	*Skewness*	*Kurtosis*
$\bar{x}_g = exp\frac{\sum f \ln m_m}{100}$	$\sigma_g = exp\sqrt{\frac{\sum f(\ln m_m - \ln \bar{x}_g)^2}{100}}$	$Sk_g = \frac{\sum f(\ln m_m - \ln \bar{x}_g)^3}{100 \ln \sigma_g^3}$	$K_g = \frac{\sum f(\ln m_m - \ln \bar{x}_g)^4}{100 \ln \sigma_g^4}$

Sorting (σ_g)		*Skewness* (Sk_g)		*Kurtosis* (K_g)	
Very well sorted	<1.27	Very fine skewed	< -1.30	Very platykurtic	<1.70
Well sorted	1.27 - 1.41	Fine skewed	-1.30 to -0.43	Platykurtic	1.70 - 2.55
Moderately well sorted	1.4 - 1.62	Symmetrical	-0.43 to 0.43	Mesokurtic	2.55 - 3.70
Moderately sorted	1.62 - 2.00	Coarse skewed	0.43 to 1.30	Leptokurtic	3.70 - 7.40
Poorly sorted	2.00 - 4.00	Very coarse skewed	> 1.30	Very leptokurtic	>7.40
Very poorly sorted	4.0 - 16.00				
Extremely poorly sorted	>16.00				

A.4 Associations between quantities of fine sediment and explanatory variables.

Negative significant correlations (p<0.01) were observed between the quantities of fine sediment presence in the investigated gravel beds of chalk streams and their stream power. Positive significant correlations (p<0.01) were also observed between the quantities of fine sediment presence in the investigated chalk streams and the occurrence agricultural land.

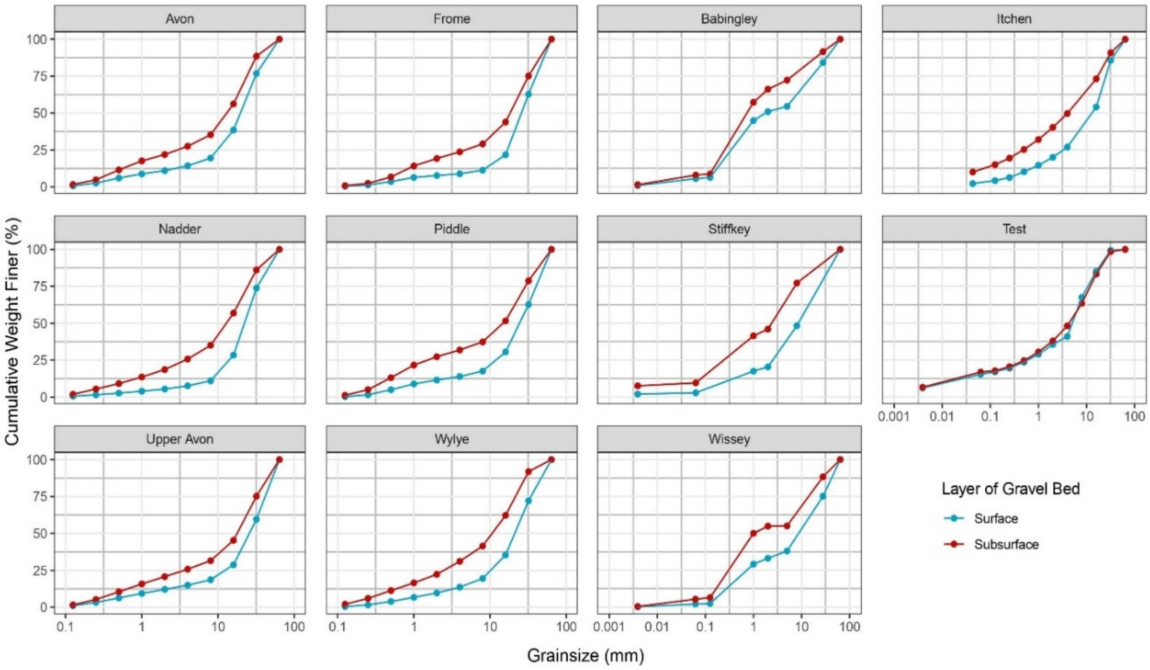
Spearman's rank correlation between proportions of fine sediment within the investigated chalk stream gravel beds and potential explanatory variables (values with significant levels p<0.01 are indicated by *).



Proportion of fine sediment	*Stream power (Wm^{-1})*	*Framework D_{50} (mm)*	*Catchment land-use (%)*			
			Arable	*Grassland*	*Arable & grassland*	*Woodland*
Bulk (0 – 40 cm)	-0.39*	-0.66*	0.26*	-0.12	0.38*	0.08
Surface (0 – 10/15 cm)	-0.47*	-0.82*	0.26*	-0.15	0.37*	0.06
Subsurface (10/15 – 40 cm)	-0.41*	-0.72*	0.29*	-0.12	0.45*	0.06

A.5 Mean GSD for investigated chalk streams

Mean GSD curves for each of the chalk stream gravel beds investigated, coloured by surface (0 – 10 cm) and subsurface (10 – 40 cm) layers, as depicted in the figure legend. The Rivers Babingley and Wissey are separated by surface (0 – 15 cm) and subsurface (15 – 30 cm) layers based on data reported in the original investigation.



Appendix B Supplementary material for Chapter 5

B.1 Kuhnle et al. (2016) - Cleanout depth model

Model proposed by Kuhnle et al. (2016) to prediction the cleanout depth of sand-sized fine sediment from an immobile gravel bed, based on bed shear stress and the CPDG (cumulative probability distribution of gravels) of the bed. Calculation of constant c:

$$c = 0.023(\frac{d}{RGT})^{-0.749}$$

$$RGT = z_{100} - z_1$$

where d is the median diameter of the fine sediment, z_{100} is the elevation of the top of the highest grain on the bed, z_1 is the elevation for the CPDG for which 99% of the measured elevations are higher, RGT is the roughness geometry thickness. Calculation of $A(\tilde{z}_s)$, the value of the CPDG at the elevation of the sand interface:

$$A(\tilde{z}_s) = \left[\frac{c^2 v_f^2 \rho}{\tau_b}\right]^2$$

where v_f is the fall velocity of the fine sediment, ρ is the density of water and τ_b is the bed shear stress. Calculation of $\tilde{z}_s$, the dimensionless cleanout depth from CPDG graph (Inverse of CPDG or the quantile function):

$$\tilde{z}_s[A(\tilde{z}_s)] = [CPDG(\tilde{z})]^{-1}$$

Calculation of cleanout depth, z_s:

$$\tilde{z}_s = 1 - \frac{z_s - z_1}{z_{100} - z_1}$$

$$z_s = \tilde{z}_s \; x \; RGT$$

B.2 Stradiotti et al. (2020) – Maximum cleanout depth model

Model proposed by Stradiotti et al. (2020) to predict the maximum cleanout depth of fine sediment from an immobile gravel bed (z_{max}), based on characteristics of the flow and the fine and coarse fractions of the sediment. Calculation of the dimensionless grain size (d_*):

$$d_* = d_{50}(\frac{Rg}{v^2})^{\frac{1}{3}}$$

where d_{50} is the median sediment diameter of the fine sediment, R is the relative density ($R = (\rho_s - \rho)/\rho$, where ρ_s is the sediment density and ρ is the density of the water), g is the acceleration due to gravity (9.81 ms^{-2}) and v is the kinematic viscosity. Calculation of the critical Shields parameter for incipient motion (θ_{cr}) for the dimensionless grain size:

$$\theta_{cr} = 0.22 d_*^{-0.9} + 0.06\left(10^{-7.7 d_*^{-0.9}}\right)$$

Calculation of the Shields parameter (θ_0) for the fine sediment:

$$\theta_0 = \frac{u_{*0}^2}{g d_s}\left(\frac{1}{R}\right)$$

where u_{*0} is the shear velocity at the gravel crest level and d_s is the characteristic grain size of fine sediment (equal to d_{50} in this instance). Calculation of the dimensionless excess of shear stress at the gravel crest (T_0):

$$T_0 = \frac{\theta_0 - \theta_{cr}}{\theta_{cr}}$$

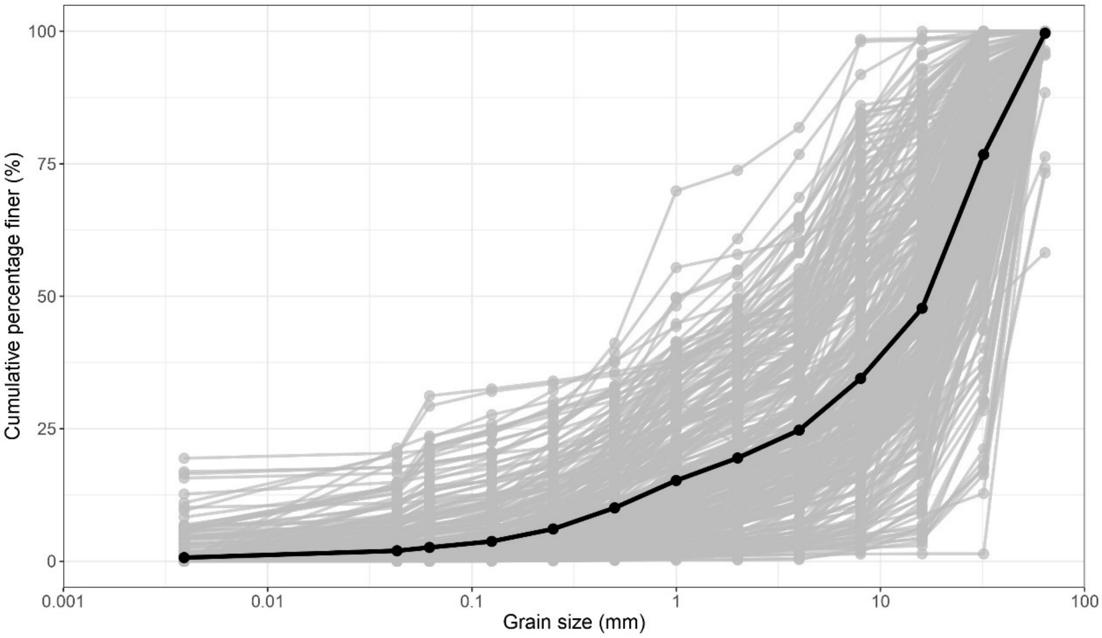
Calculation of z_{max}, maximum depth of erosion of fine sediment, only valid for values of u_{*0} for which coarse material does not move:

$$z_{max} = D_{90}(-a T_0^b)$$

where D_{90} is the bed particle diameter for which 90% of particles are finer and a and b are coefficients based on the original studies data (a – 0.32 and b – 0.37).

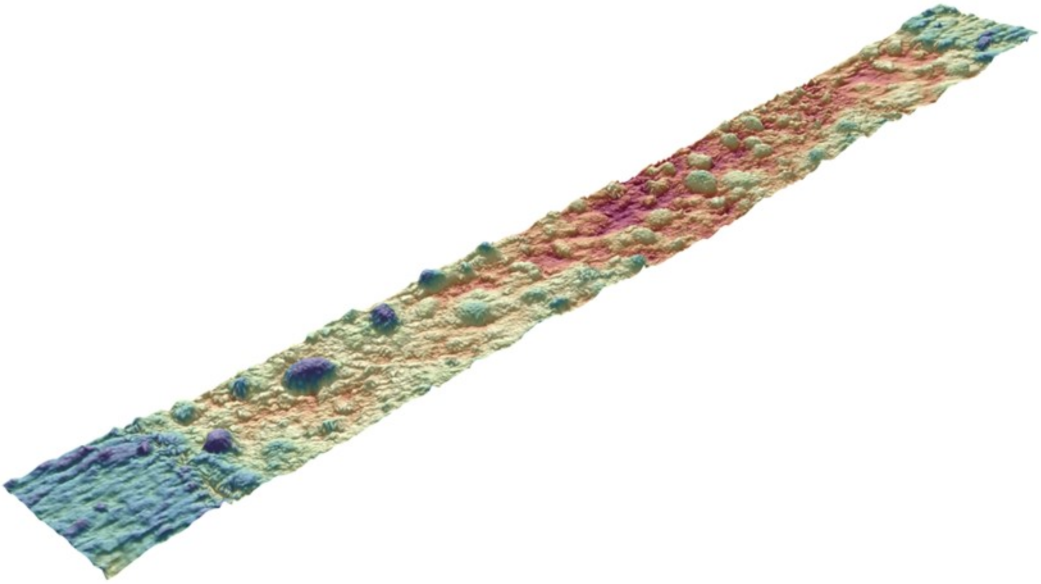
B.3 GSD of the artificial gravel bed

GSD of the artificial gravel bed used within the flume experiments (black line), which was calculated as the mean of the surface layer (0 – 20 cm) GSDs from 90 gravel bed freeze-coring sites from 11 chalk streams across the UK (grey lines) (Section 4.5.1).



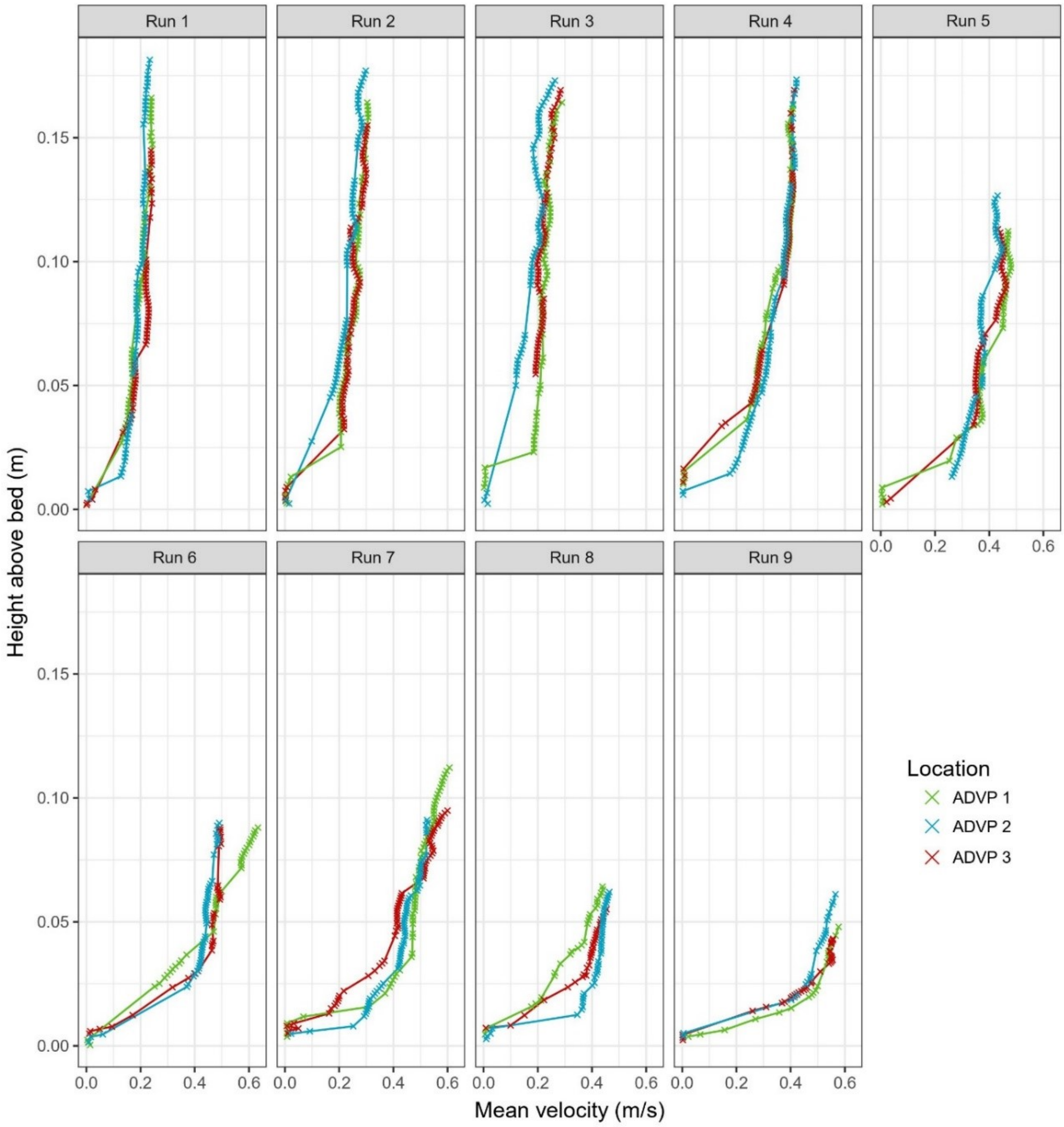
B.4 Terrestrial laser scan of flume

Terrestrial laser scan of artificial chalk stream gravel bed post experimental flume run 9.



B.5 Velocity profiles

Velocity profiles for each of the three ADVP recording locations for each of the experimental flume runs.



B.6 Measured shear velocities and bed shear stresses from flume experiments

Measured shear velocities, height above the bed and bed shear stress for each of the three ADVP location in each of the experimental runs (u^* - shear velocity (m s^{-1}), z_0 – height above the bed (m), τ_0 – bed shear stress (Pa)).

Run	*ADVP 1*			*ADVP 2*			*ADVP 3*		
	u^*	z_0	τ_0	u^*	z_0	τ_0	u^*	z_0	τ_0
Run 1	0.0247	0.0034	0.6120	0.0261	0.0030	0.6809	0.0211	0.0021	0.4470
Run 2	0.0334	0.0071	1.1150	0.0322	0.0052	1.0381	0.0307	0.0067	0.9429
Run 3	0.0365	0.0075	1.3303	0.0355	0.0028	1.2615	0.0351	0.0047	1.2331
Run 4	0.0601	0.0042	3.6153	0.0581	0.0044	3.3781	0.0468	0.0042	2.1870
Run 5	0.0643	0.0104	4.1302	0.0684	0.0116	4.6769	0.0545	0.0019	2.9689
Run 6	0.0658	0.0033	4.3358	0.0677	0.0034	4.5892	0.0584	0.0022	3.4105
Run 7	0.0838	0.0069	7.0232	0.0867	0.0069	7.5133	0.0751	0.0045	5.6475
Run 8	0.0778	0.0068	6.0509	0.0790	0.0051	6.2393	0.0730	0.0060	5.3336
Run 9	0.0915	0.0031	8.3676	0.0923	0.0034	8.5114	0.0857	0.0036	7.3487

B.7 Cheng (2011) - Hydraulic radius sidewall correction

Correction of hydraulic radius by Cheng (2011):

$$f_{\omega} = 31\left[\ln(1.3\frac{R_e}{f})\right]^{-2.7}$$

$$R_e = \frac{VD}{v}$$

$$f = \frac{8grS}{V^2}$$

$$f_b = f + \frac{2h}{B}(f - f_{\omega})$$

$$r_b = \frac{f_b}{f}r$$

where, R_e – hydraulic diameter, D = 4r, where r is the hydraulic radius (A/P, where A is the cross-section area of the flow (m^2) and P is the wetted perimeter (m)), f is the bulk friction factor, V is the cross-sectional average velocity, S is the energy slope and g is the acceleration due to gravity (9.81 ms^{-2}), h is the flow depth, B is the channel width, r_b is the hydraulic radius in the presence of sidewalls.

B.8 Cheng (2000) - Fall velocity model

Calculation of fall velocity used by Kuhnle et al. (2016), proposed by Cheng (2009):

$$d_* = (\Delta \frac{g}{v^2})^{\frac{1}{3}} d$$

$$\Delta \; = (\rho_s - \rho)/\rho$$

$$C_D = \frac{432}{d_*^3}(1 + 0.22d_*^3)^{0.54} + 0.47[1 + \exp{(-0.15d_*^{0.45})}]$$

$$\omega_* = \sqrt{4d_*/(3C_D)}$$

where d is the particle diameter, ρ_s is the sediment density, ρ is the water density, v is the kinematic viscosity of water and g is the acceleration due to gravity (9.81 ms^{-2}).

B.9 Wooster et al. (2008) – Porosity predictor

Porosity of gravel bed predictor proposed by Wooster et al. (2008):

$$n = 0.621e^{-0.457\sigma_{gg}}$$

where σ_{gg} is the standard deviation of the gravel bed grain size distribution.

Appendix C Supplementary material for Chapter 6

C.1 Original flow velocity studies

Overview of the original studies used to compile the depth averaged velocities from chalk streams used in Figure 6.1, detailing the purpose of the original study, sampling techniques and localised spatial distribution of samples.

Study	*Chalk stream*	*Time of year*	*Reason for study*	*Sampling design*	*Sampling technique*
Marshall and Westlake (1990)	Bere stream	Autumn (October, November, December)	The influence of instream aquatic macrophytes on flow velocities.	Water velocities were measured at 50 mm depth intervals to create the velocity profiles. Multiple water velocity profiles were made across the channel at 0.5 m intervals.	Water velocities measured using an Edington current meter with a 10 mm propeller.
Green (2005)	River Wylye	Summer (July)	The influence of instream aquatic macrophytes on flow velocities.	Water velocities were measured at 50 mm depth intervals to create the velocity profiles. Water velocity profiles were made at 1 m intervals downstream and multiple points across the vegetation patch.	Water velocities measured using a two-dimensional electromagnetic current meter (EMCM).
Gurnell et al. (2006)	River Frome	Spring & Summer (March, April, June & August)	Interactions between aquatic plants, flow velocities and bed substrate.	Measurements taken at 40% of the water depth at 1 m intervals across the channel at 10 evenly spaced cross-sections.	Sampling techniques not detailed in the original study.
Wharton et al. (2006)	Bere stream	Spring, Summer, Autumn & Winter (April to December)	Impacts of instream vegetation and invertebrates on flow velocities.	Multiple water velocity profiles were made across the channel at 0.5 m intervals. Velocities measured over 60 second periods. Water velocities were measured at 50 mm depth intervals to create the velocity profiles.	Water velocities were measured using a temperature constant anemometry system (CTA).

C.1 continued:

Warren et al. (2009	Bere stream	Summer (June & July)	Transport of organic fine sediment in vegetated channels.	Water velocities were measured at 40% of the water depth at 0.5 m intervals across the channels along each of the nine transects.	Water velocities were measured using an electromagnetic flow meter (flat sensor type; Valeport).
Grabowski (2011)	Bere stream & River Frome	Autumn, Winter, Spring, Summer (September, November, January, March, May, July).	The erodibility of fine sediment deposits.	Water velocities were measured at 40% of the water depth at 0.5 m intervals across the channels along each of the transects.	Water velocities were measured using a Valeport Model 801 (Flat) EM flow meter.
Old et al. (2014)	Lambourne	Spring & Summer (May & July).	The influence of weed cutting on instream and riparian conditions.	Multiple water velocity profiles were made across the channel at 1 m intervals. At each profile location, six measurements were taken between the bed and the water surface.	Water velocities were measured using an electromagnetic flow meter.
Mullen (2016)	Lambourne, Kennet & Winterbourne	Spring & Summer (May & June).	Influence of drought and drought recovery conditions on macroinvertebrate communities.	Water velocity profiles constructed using measurements taken a 40% of the water depth and 2.5 cm above the substratum.	Measured using a Doppler flow meter.

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