**The scope for a system-based approach to determining fine sediment targets for chalk streams**

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**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 excessive 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 excessive 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.

**Key Words**

Chalk stream, fine sediment, sediment budget, gravel-bed, sediment targets

**1. Introduction**

Elevated levels of fine sediment, defined as inorganic and organic particles <2 mm in diameter, have been identified as one of the principle 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 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 European Union (EU) Freshwater Fish Directive 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 (*Salmo salar* L.) and white-clawed crayfish (*Austropotamobius pallipes*) (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 record significantly higher proportions of fine sediment compared to other gravel bedded 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 winter-sown 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 or 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; for example, the role of aquatic macrophytes within the sediment budget of chalk streams is well established (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; Rosewarne *et al.,* 2014; Berli *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.*, 2017). 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.

**2. 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 1).



Figure 1: Distribution of chalk geology and the occurrence of chalk streams within the UK. Data accessed (British Geological Survey, 2008; Ordnance Survey, 2020).

***2.1. Chalk stream hydromorphology***

Chalk streams are predominantly groundwater-fed 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 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 record 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).

***2.2. 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 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.



Figure 2: A generic chalk stream timeline, detailing significant periods of human modifications that have resulted in changes in chalk stream systems and their catchments (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, 2007; Johannsen and Armitage, 2010; Grabowski and Gurnell, 2016; Evans, 2017). In addition, chalk stream catchments tend to 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 runoff 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, for example, on the wheelings used 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 bed 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 in-stream macrophyte communities. Concomitantly, this also removed riparian buffering, further increasing land surface to river network connectivity, and increasing inputs of fine sediment.

***2.3. Ecology of chalk streams***

The characteristics of chalk streams provide unique habitats for a wide range of aquatic 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 flow 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 in-stream 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 1).

Table 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).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Group | Species | Winterbourne | Perennial | Designation |
| Plants | 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.*

*2.3.1. 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) that 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 in-channel 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)* (DeVries, 2012), the foraging activities of benthic fish such as bullhead (*Cottus gobio)* (Rice *et al*., 2019), and macroinvertebrates such as invasive signal crayfish (*Pacifastacus leniusculus*) (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 signal crayfish (*P. leniusculus*) (Faller *et al.*, 2016). Diatom and biofilm communities can influence bed stabilisation within the surface layers of the riverbed through the production of extracellular polymeric substances (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.

*2.3.2. 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 significant detrimental impacts on aquatic organisms (Table 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 known ecological impacts associated with elevated fine sediment in chalk streams are discussed below.

Table 2: Summary of the general impacts on aquatic organism trophic groups of elevated loads of suspended sediment and increased infiltration of fines into the stream bed.

|  |  |  |  |
| --- | --- | --- | --- |
| Trophic Level | Elevated Suspended Sediment in the Water Column | Increased Deposition and Infiltration of Fine Sediment into Gravels | Source |
| 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,b); Sutherland and Meyer, (2007); Shoup and Wahl,(2009); Berli *et al.,* (2014); Sear *et al.,* (2016); Bašić *et al.,* (2019). |

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 significant 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, Atlantic salmon (*S. salar*) and brown trout (*S. trutta*), has been well established (Greig *et al.*, 2005a, b, 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 chalk stream species require similar spawning habitats (e.g. Bullheads, *Cottus 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 (*Barbus 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 (*Austropotamobius pallipes*) gills, decreases in feeding and respiration ability (Rosewarne *et al.*, 2014), and elevated fine sediment deposition in gravel beds increasing incubating mayfly (*Serratella ignita*) 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*) 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 larval European river lamprey (*Lampetra fluviatilis* L.) recruitment (Silva *et al.*, 2015). Overall, the specific impacts of both 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.

***2.4. 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 streams regularly record 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.*, 2017). 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).

***2.5. 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, 2007; 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. 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) or river substrate metrics (Table 4). Water column metrics include turbidity, suspended sediment concentration summary statistics and sediment regimes. River substrate metrics consider substrate composition/embeddedness, intragravel 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 Water Framework Directive (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 Freshwater Fish Directive, although this is not enforced by any statutory bodies. In the UK, additional suspended sediment targets have been applied to waste water discharges from various sources such as watercress and fish farms, but apart from the target directed at water treatment work discharges (Table 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 macroinvertebrate found instream using biotic indices (e.g. Murphy *et al.,* 2015, 2017; Turley *et al.,* 2016; Extence *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: Examples of current 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 mgL-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 mgL-1 above >100 mgL-1 or 10% increase above <100 mgL-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 (South central) | Turbidity | 1-50 NTU (upland and lowland). | ANZECC (2000) |

Table 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) |
| Intragravel dissolved oxygen | 1-day minimum of 5.0 mg/L.  7-day mean ≥6.5 mg/L. | 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) |

***3.1. 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 record suspended sediment yields significantly 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 (Cooper *et al.,* 2008; Collins and Anthony, 2008b). 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, grainsize 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, *Ephemeroptera* eggs (Mayfly) experienced 45% mortality when exposed to 20 mgL-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 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 (Tables 3 and 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 stream 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 5: Examples of the ranges in critical thresholds for the effects of fine sediment on chalk stream biota (SS: suspended solids; N/A: not available: NTU: nephelometric turbidity units).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Taxon | 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 mgL-1 | *N/A* | <63 µm | *N/A* | Increased drift. | Wood *et al.*, (2005) |
| 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 mgL-1 | 1704 | 5-100 µm | *N/A* | 10-45% mortality. | Everall *et al.*, (2018) |
| Egg | 10-20 mgL-1 | 4392 | 5-100 µm | *N/A* | 20-80% mortality. | Everall *et al.*, (2018) |
| White clawed crayfish (*Austropotamobius pallipes*) | Juvenile | 42 mgL-1 | 1080 | *N/A* | *N/A* | Sediment accumulation in 92% of individuals.  25% gill area affected. | Rosewarne *et al.*, (2014) |
| Juvenile | 65-133 mgL-1 | 1080 | *N/A* | *N/A* | Sediment accumulation in 100% of individuals.  40-60% gill area affected. | Rosewarne *et al.*, (2014) |
| Atlantic salmon (*Salmo salar)* | Adult | 20 mgL-1 | *N/A* | *N/A* | *N/A* | Increased foraging. | Robertson *et al.*, (2006) |
| Adult | 60-180 mgL-1 | *N/A* | *N/A* | *N/A* | Avoidance behaviour. | Robertson *et al.*, (2006) |
| 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. | Heywood and Walling (2007) |
| Egg | 10% of red mass | *N/A* | <2 mm | 19.7 | 91.3% mean mortality. | Greig *et al.,* (2005) |
| Brown trout  (*Salmo trutta)* | Juvenile | 13 -62 NTU | *N/A* | *N/A* | *N/A* | 13-38% reduction in swimming performance. | Berli *et al.*, (2014) |

**4. Gravel bed sediment budgets as an overarching framework for informing best 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 be 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).

***4.1. Chalk stream gravel bed sediment budget framework***

We propose that the gravel bed sediment budget be separated into the controlling mechanisms for the accumulation of fine sediment present in chalk streams. The colmation of chalk stream gravels 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 (Figures 3, 4 and 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 is manifest in the channel bed sediment budget, which 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: 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.

*4.1.1. 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 winter-sown 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 runoff 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*), for example (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*) 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 winter-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.

*4.1.2. 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 mode of transport of sediment 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; Hemond and Fechner, 2015; Sear *et al.,* 2008). Bedload transport consists of particles that when mobilised remain in near continual contact with the gravel bed and generally consists of coarser sediments (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 sediment load in is carried in suspension (Sear *et al.,* 1999). In these conditions, chalk stream gravel bed 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 modification 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 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) during summer months in chalk stream can maintain higher velocities despite lower discharges (Wharton *et al.,* 2006).



Figure 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.

*4.1.3. 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 the 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 and shear stress of the chalk stream, suspended sediment concentrations, hydraulic gradient of the seepage flow, grainsize 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 grainsize distributions of the ingressing fine sediment and the gravel bed framework has been demonstrated to be a controlling factor in the initial particle 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 percolation 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 relativity high both during 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), including increased roughness induced by aquatic macrophytes, large woody debris, 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 extracellular polymeric substances (EPS) within the gravel framework can reduce the quantity and infiltration depth of deposited sediment via the blocking of intra-gravel pores (Salant, 2011).

*4.1.4. 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 flushed 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 bed mobilising flows, intra-gravel flows and arrangement of bed sediments are the dominant factors (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 sediment 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 particle 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 re-entrainment (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 woody debris. 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 threshold 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). 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 altered 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 the gravel bed framework and 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; 2017; Rice *et al.,* 2016; 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.

***4.2. The role of ecosystem engineering controls for chalk stream gravel bed sediment budgets***

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 yet a growing body of scientific literature highlights their importance for all four mechanisms (Figure 2) of the channel system 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 the riverbed, Mechanisms A and C (e.g. signal crayfish burrowing in riverbanks).
2. Modifying the erodibility of sediment deposited on the riverbed, Mechanisms B and C (e.g. redd cutting by salmonids).
3. Modifying the rate of sediment accumulation and residence time on, or in, the riverbed, 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 organisms can have substantial effects on sediment processes within chalk streams and, consequently, influence the four mechanisms (Figure 5) that determine the gravel bed sediment budget of chalk streams (Table 6).

Table 6: Examples of the influence of ecosystem engineers found in chalk streams on the four critical mechanisms (A, B, C and D; Figure 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 | Source |
| 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 mechanims C.  Increases mechanism D. | Mason *et al.*, (2019) |
| 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 mechanisn 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 mechanim D. | Kondolf *et al.,* (1993) |



Figure 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*) introduces sediment from the banks into the channel system; a sediment source that is otherwise relativity unimportant within chalk streams (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 in the sediment budget 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 velcocities and shear stress (Mechanism B) within aquatic macrophytes increases sediment deposition and infiltration (Mechanism C) and decreases sediment exfiltration and resuspension (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*) 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 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).

**5. Prospects**

In chalk streams, low bed mobilising flows have resulted in propensity for high quantities of fine sediment accumulation in 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 of 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 woody debris to encourage rates of 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 winter-sown cereal production. Consequently, the ecological impacts arising from fine sediment are expected to be greater.

**6. 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 sediment. The accumulation of fine sediment within the gravel beds of chalk streams has pronounced detrimental impacts on their ecology as a consequence of the inability of such 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 rate 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 bed material transport deposit and accumulate in the bed that controls fine sediment pressure. The absence of bed mobilising flows and high sediment-associated organic matter loads combine to 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 gravels 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 assessed.

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