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RESEARCH ARTICLE

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

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Abstract

Elevated fine sediment accumulation in a river system's gravel bed is known to cause detrimental ecological impacts. Current sediment targets and approaches to mitigation have failed due to the oversimplification of geomorphological processes controlling fine sediment accumulation and the lack of relevant scientific knowledge underpinning them. This is particularly apparent in chalk streams (groundwater-dominated systems) which regularly exhibit high rates of sediment accumulation despite low suspended sediment yields. A necessary first step is to better characterise their sedimentology; 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 We collated published and unpublished freeze-core data, encompassing 90 sites across 11 UK chalk streams. Results showed average quantities of fine sediment (<2 mm) in chalk stream gravel beds were 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. Additionally, a major contrast was identified between experimental conditions in flume studies used to establish models describing interactions/mechanisms 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 predict the outcome of such management techniques correctly in a real-world situation.

KEYWORDS
colmation, fine sediment targets, river restoration, riverbed substrate, sediment budget

1 | INTRODUCTION

Fine sediment (inorganic and organic particles <2 mm in diameter) plays a fundamental role in freshwater systems. This includes in their hydrogeomorphic cycles, habitat heterogeneity and for the delivery of nutrients, dissolved organic matter and contaminants such as microplastics and heavy metals (Chon et al., 2012; He et al., 2021; Owens et al., 2005; Westrich & Förstner, 2007). However, excessive fine sediment quantities 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., Bašić et al., 2019; Bo et al., 2007; Robertson et al., 2006; Rosewarne et al., 2014; Sear et al., 2016). Sediment targets have been proposed to guide the management of the fine sediment problem and can currently be split into two distinct categories (Collins et al., 2011): firstly, water column metrics, such as turbidity levels and suspended sediment concentrations and secondly, river substrate metrics, such as substrate composition/embeddedness, riffle stability and intragravel dissolved oxygen concentration (Mondon et al., 2021). Few sediment targets are based on suspended sediment concentrations, despite their relevance for fine sediment accumulation (Collins et al., 2011; Mondon et al., 2021). Targets based on suspended sediment concentrations (e.g., the repealed European Union (EU) Freshwater Fish Directive 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 (Mondon et al., 2021). Fundamentally, many proposed targets for sediment management in freshwater systems have been oversimplified through a lack of consideration of differences in hydro-sedimentological responses (Collins & 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 (Mondon et al., 2021).

Chalk streams are defined as groundwater-dominated systems, with a base-flow index (river flow derived from groundwater chalk aquifers) exceeding 75% and a course that runs primarily over basal chalk geology (Mondon et al., 2021; O'Neill & Hughes, 2014). Approximately 85% of the global chalk streams occur within the United Kingdom, located across a chalk outcrop from Dorset to East Yorkshire. They also occur in France, Belgium and Denmark (Mondon et al., 2021; O'Neill & Hughes, 2014). 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; Mondon et al., 2021). 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 (*Salmo salar*), Brown trout (*Salmo trutta*) and Bullhead (*Cottus gobio*) (Greig et al., 2007; Louhi et al., 2008; Tomlinson & Perrow, 2003). However, chalk streams regularly display higher fine sediment quantities within their gravel beds compared with other gravel-bed systems nationally (Acornley & Sear, 1999; Dunscombe et al., 2018; Milan et al., 2000; Sear et al., 2008). 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 & 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., Everall et al., 2018; Greig, Sear, & Carling, 2005; Heywood & Walling, 2007; Rosewarne et al., 2014). Elevated fine sediment accumulation has resulted from the intensification of agriculture and farming practices within chalk stream catchments, increasing fine sediment inputs (Collins & Zhang, 2016; Grabowski & Gurnell, 2016; Walling & Amos, 1999). In this regard, the shift to winter-sown cereal production and amalgamation of smaller fields into larger fields, have increased runoff pathway length and velocity, erosion and connectivity between hillslope surfaces and river networks (Boardman, 2013; Boardman et al., 2019; Evans, 2017; Grabowski & Gurnell, 2016; Johannsen & Armitage, 2010). In addition, centuries of in-stream activities such as the construction of weirs and over-abstraction of chalk aquifers have reduced discharges and flow velocities, further limiting bed mobility and contributing to elevated fine sediment accumulation (Bickerton et al., 1993; Petts et al., 1999; White et al., 2021; Wood & Armitage, 1999).

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 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 (Water Framework Directive) (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 & Zhang, 2016; Mondon et al., 2021; Naden et al., 2016), 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.

2 | METHODS

2.1 | Database of chalk stream study sites

All streams investigated in this study are identified as chalk streams. Data on the composition and structure of chalk stream gravel beds were collated from previous field-based studies and reports. The main determinator of whether data were appropriate for this study was the inclusion of grain size distribution (GSD) and division of a sediment sample into a pre-determined number of size fractions. Subsequently, 12 UK-based field 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. However, a number of these 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. For the present study, freeze-coring techniques (Carling & Reader, 1981; Petts et al., 1989; Walkotten, 1976) are more suitable: freezing of bed sediment and interstitial water in situ prevents fine sediment loss. Vertical sections of the substratum preserved by freeze-coring also allow for the determination of vertical variations in sedimentological characteristics. Consequently, the decision was taken to only consider samples that had been collected using freeze-coring techniques: data assembled using alternative techniques such as bulk sampling and use of artificial redds (e.g., Acornley & Sear, 1999; Heywood & Walling, 2007) were not considered further. Any sites that had experienced any form of documented riverbed restoration, including gravel cleaning and/or the artificial augmentation of gravel, were also excluded.

The overall dataset meeting these criteria, subsequently, comprised 90 field sampling sites (Figure 1), encompassing 195 freeze-core samples, across 11 chalk streams and their tributaries, from 10 studies (Acornley & Sear, 1999; Barron, 1992; Bateman, 2012; Beaumont et al., 1993; Carling, 1983; Greig, Sear, & Carling, 2005; Milan, 1994; Mitchell, 2015; Riley et al., 1999). These ranged from the River Piddle in Dorset, South England, to the River Babingley in Norfolk, East England (Figure 1). The relevant data from each of these studies were extracted from GSD tables and/or graphical readings of cumulative frequency curves from corresponding papers. Where available, data appertaining to the chalk stream's physical characteristics were also extracted; however, where this was not stated, information was compiled from alternative sources (Table 1).

2.2 | Data analysis

GSDs based on the logarithmic Wentworth scale of particle sizes (Appendix A) were used to compare gravel bed sediments and were characterised by 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 the symmetry of distribution and (4) kurtosis, degree of concentration of grains relative to the average (Bunte & Abt, 2001). A range of cumulative percentile values (grain size for which the specified percentage of grains is coarser) such as the median (D_{50}) was also used to compare bed sediments. Several of the original investigations reported these parameters; unreported statistics were calculated using the mathematical 'Geometric method of moments' (Appendix B) in the Gradistat programme (Blott & 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 C).

Models describing the mechanisms of fine sediment accumulation in immobile gravel beds are explored in the Supporting Information S1. Based on their limitations as discussed, the following models were deemed most suitable to describe the condition occurring in chalk stream gravel beds. Saturation states of the gravel beds were determined using Equation 1, proposed by Wooster et al. (2008), which quantifies the maximum quantity of fines that can infiltrate a bed before it is no longer considered '*framework-supported*' (i.e., the framework bed particles are not in tangential contact and interstitial fines represent >30% of the total bed weight (Carling & Glaister, 1987; Wilcock & Kenworthy, 2002)):

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

where f_s is the saturated fine sediment fraction (FSF), σ_{gg} and σ_{sg} are the geometric standard deviations for the framework sediment and infiltrating sediment, respectively and D_{gg} and d_{sg} are the geometric means of the framework sediment and infiltrating sediment, respectively. Infiltration mechanisms of fine sediment in chalk stream gravel beds were determined using Equation 2, proposed by Gibson et al. (2010): (2.1) bridging, infiltrating fines are larger than the framework pore throats and form a clogged surface layer; (2.2) unimpeded static percolation (USP), infiltrating fines are smaller than the interstitial spaces in the bed framework and subsequently, percolate downwards to an impermeable layer and then fill upwards through the bed and (2.3) transition, a combination of both bridging and USP (Gibson et al., 2009, 2010; Herrero & Berni, 2016) (further discussed in the Supporting Information S1):

$$\begin{aligned} &\frac{D_{15\,Framework}}{d_{85\,Matrix}} < 12 - \textit{Bridging} \quad (2.1) \\ &\frac{D_{15\,Framework}}{d_{5\,Matrix}} > 14 - \textit{Unimpeded static percolation}\,(USP) \quad (2.2) \\ &12 < \frac{D_{15\,Framework}}{d_{85\,Matrix}} < 14 - \textit{Transition} \quad (2.3) \end{aligned} \qquad (2)$$

where, $D_{15\,Framework}$ is the particle size for which 15% of the framework particles are finer and $d_{85\,matrix}$ is the particle size for which 85%

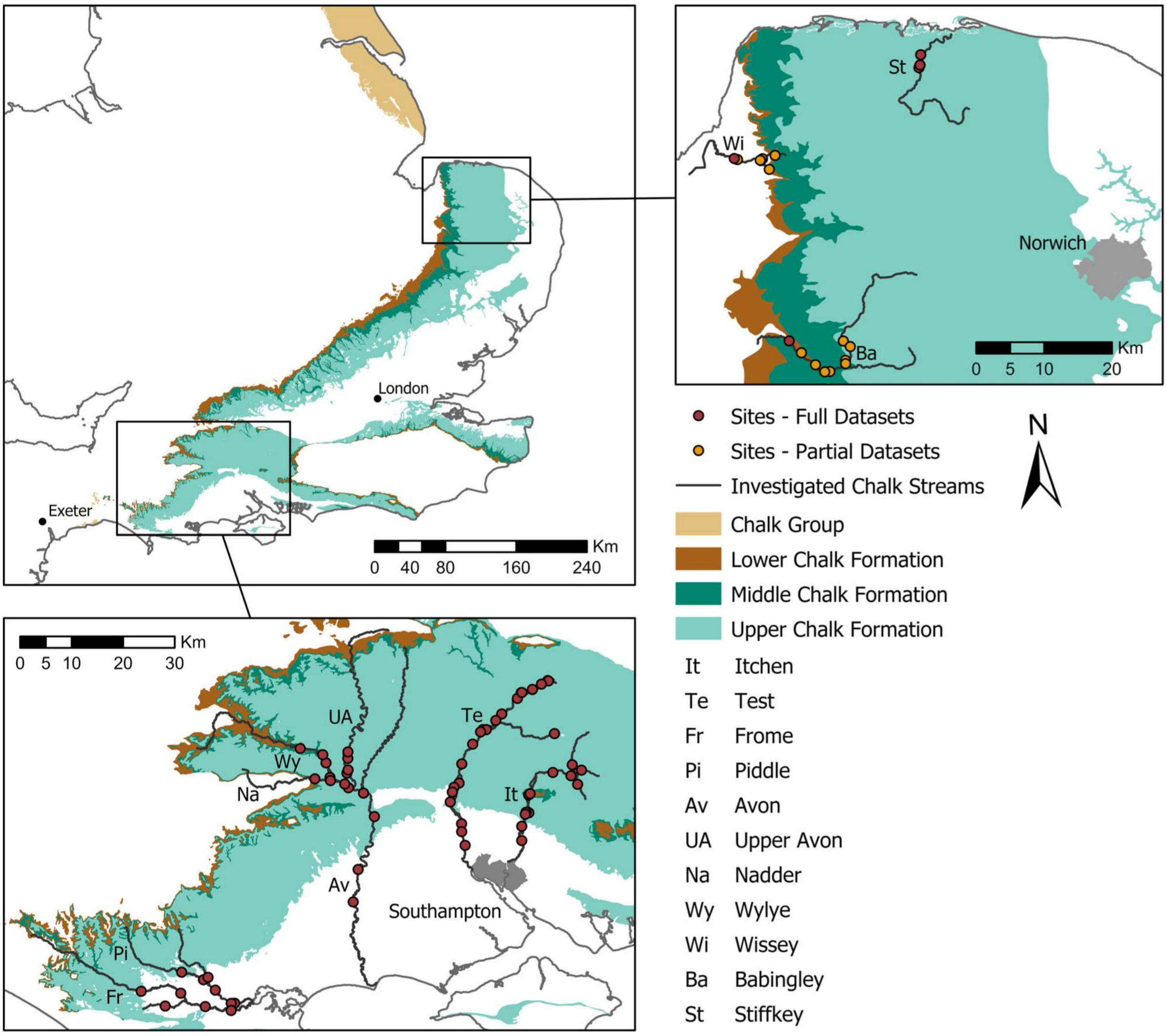

FIGURE 1 Location of the chalk stream gravel bed field sampling sites investigated in this study. [Color figure can be viewed at wileyonlinelibrary.com]

of the fine sediment particles are finer. In the original determination of Equations 1 and 2, the gravel beds were initially void of fine sediment and the influence of silt and clay-sized 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 a bed framework initially void of interstitial fines and matrix material (2 mm > *d* > 62 µm), representative of fine sediment >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 & Glaister, 1987; Church et al., 1987; Bunte & Abt, 2001; Wilcock & Kenworthy, 2002; Frings, 2011). Finally, the determined sedimentary characteristics of chalk streams were compared with the conditions in flume experiments (Appendix D), used to determine models describing the mechanisms of fine sediment infiltration and accumulation in immobile gravel beds.

3 | CHARACTERISTICS OF GRAVEL BEDS IN THE CHALK STREAM DATABASE

3.1 | Gravel bed structure

A wide range of grain sizes was found in the chalk stream beds examined, from boulders (>128 mm) to clay (<3.9 µm). 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 2); exceptions are the Rivers Babingley and Wissey

TABLE 1 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^3s^{-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.

TABLE 2 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 1), Ave – Average, D_g – Geometric mean grain size, 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

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 2a). The average bulk D_{50} of the gravel beds was 13.95 mm (0.5–33.86 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.

The average chalk stream framework D_{50} was 19.67 mm (6.46–37.44 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 River Test had >99% of the 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 framework consisting of particles >32 mm (Figure 2a). Average quantities of matrix material as a proportion of

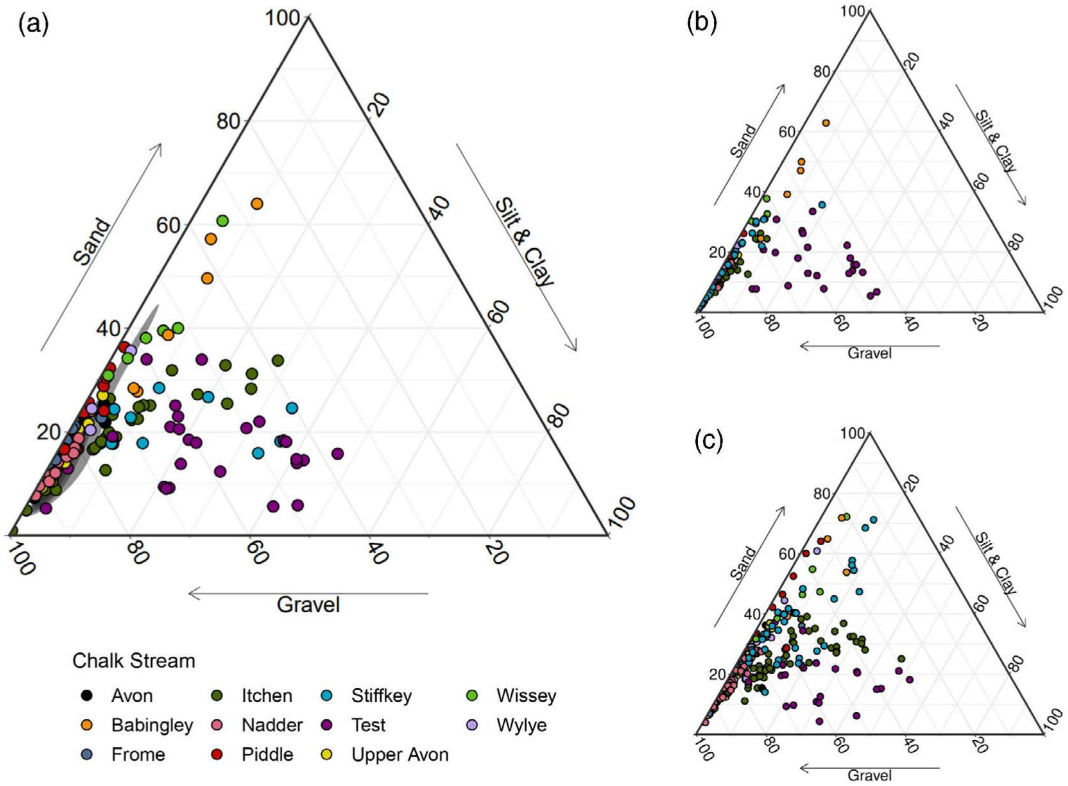

FIGURE 2 Percentages of gravel (d > 2 mm), sand (2 mm < d > 62 μm) and silt and clay (d < 62 μm) in the investigated chalk stream gravel beds in; (a) overall deposits (0–40 cm), (b) surface layers (0–10/15 cm) and (c) subsurface layers (10/15–40 cm). Points are grouped by individual chalk streams as 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 & Walling, 1988; Milan, 1994; Quin & Williams, 1999; Quin & Williams, 2000; Greig, Sear, & Carling, 2005; Twine, 2013). [Color figure can be viewed at wileyonlinelibrary.com]

total bed weight were 24% (1%–73%). Out of 195 beds investigated, 28 (14%) had matrix proportions >40% of the total bed weight and can be considered *matrix-supported* deposits. 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 fine sediment >30% of the total bed weight, suggesting that neither of these rivers have *framework-supported* gravel beds. Notably, the Rivers Babingley, Wissey and Stiffkey had substantially higher quantities of medium sand (1–0.125 mm), >70%, compared with the Rivers Itchen and Test at 42% and 31%, respectively. The Rivers Itchen and Test, however, had higher quantities of silts and clays (<62 μm), 38% and 47%, 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 amount (92%).

3.1.1 | Surface vs. subsurface

Of all the gravel beds, 88% were characterised by a coarse surface layer (Table 3), with higher bulk D_{50} and lower fine sediment quantities in surface layers compared with subsurface layers. The presence of a coarse layer can be quantified as the ratio between surface D_{50} and subsurface D_{50} (Bunte & Abt, 2001), defined as an armour ratio. The armour ratio varied across the systems and was highest on the Rivers Babingley, Wissey and Stiffkey and lowest on the River Test. Over half the sites with armour ratios of less than one were present on the River Test, as evident from the minimal differences between the surface and subsurface GSD (Appendix E). All the other systems had a distinctive coarse-grained surface layer, a finer subsurface layer, and a coarser bulk D_{50} (Table 3). On average, the quantity of fine sediment as a proportion of the bed layer in surface layers was 17% (Figure 2b; 0.26%–68%). However, the 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% (Figure 2c; 4.5%–87%). 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.

3.2 | Vertical variation of fines

Vertical variations of fine sediment quantities illustrated an overall increasing trend with increasing gravel bed depth (Figure 3);

TABLE 3 Bulk (framework and matrix) sediment characteristics for surface (0–10/15 cm) and subsurface (10/15–40 cm) layers in each of the chalk streams investigated. (D_{50} – Median particle size, D_g – Geometric mean grain size, $P_{2.0}$ – Proportion of fine sediment <2 mm).

	Surface (0–10/15 cm)			Subsurface (10/15–40 cm)			
Chalk stream	D_{50}	D_g	$P_{2.0}$	D_{50}	D_g	$P_{2.0}$	Armour ratio
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[a]	11.23		33.08	2.78		54.85	4.04
Babingley[a]	5.86		50.88	1.63		66.05	3.61
Stiffkey[a]	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

[a]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.

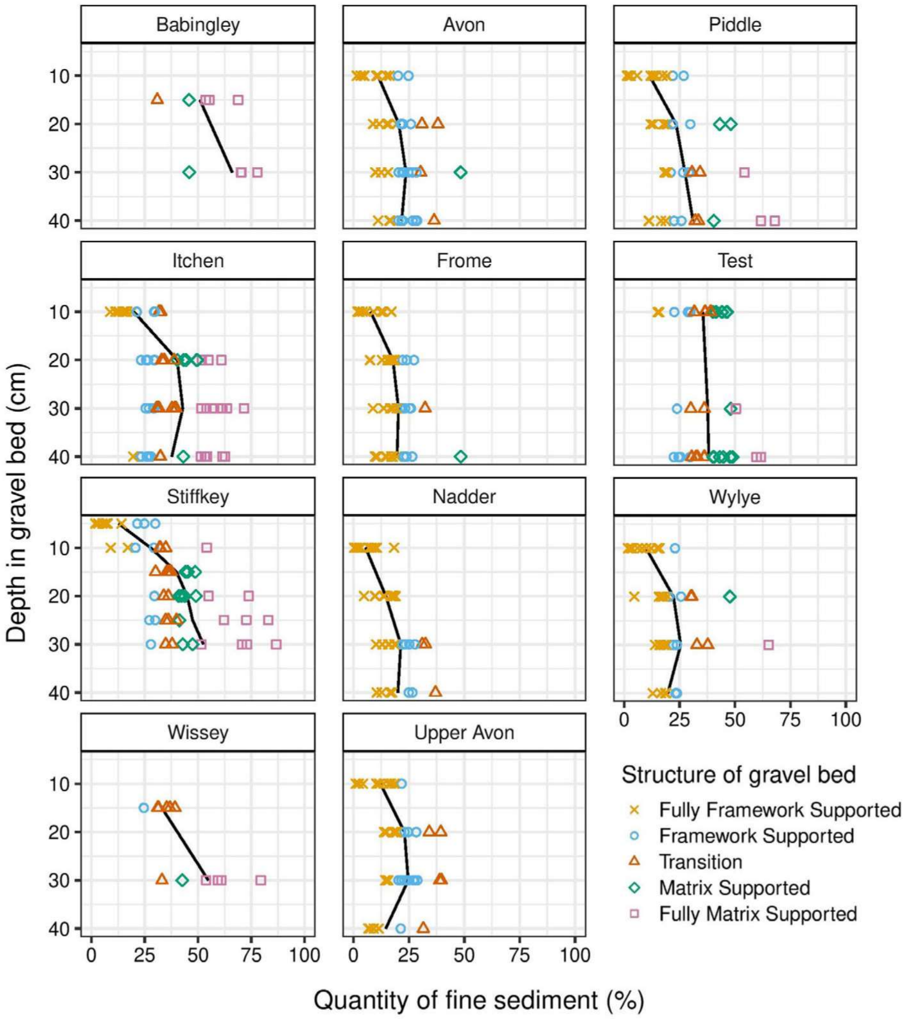

FIGURE 3 Quantities of fine sediment (<2 mm) as a proportion of individual gravel bed layers for each of the investigated chalk streams (data are only shown where available for individual bed layers in the original investigations). Points are grouped by gravel bed structure, determined by the quantity 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. [Color figure can be viewed at wileyonlinelibrary.com]

increasing, on average, by 90% between surface and deepest subsurface layers. 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. The highest increases in fine sediment quantities were observed between the surface and first subsurface layers, 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, these increases in fine sediment quantities were >100%. Increases in fine sediment quantities were less substantial between deeper bed layers (10–20/20–30 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 was either FFWS or FWS (71%), 14% were in T and 15% were either MS or FMS (Figure 3). 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 (0–10/0–15 cm) 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 0% in the deepest subsurface layers (30–40 cm).

3.3 | Saturation of beds

A greater proportion of gravel beds were over-saturated with fine sediment; 162 (89%) compared with 21 (11%) under-saturated beds (Figure 4a). 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 the surface (0–10 cm) and subsurface layers (10–40 cm) (Figure 4b & 4c), 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.

3.4 | The occurrence of infiltration mechanisms

Out of all the gravel beds investigated, 4.5% experienced USP or were in transition, where both USP and bridging are occurring (Figure 5; 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 decrease 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, beds 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 5a). 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, 20–30 and 30–40 cm bed layers.

3.5 | Field vs. experimental data

Comparison between the vertical distribution of infiltrating fine sediment in immobile gravel beds in experimental flume studies (Appendix D) with those found in chalk stream gravel beds (Figure 3), demonstrates contradictory trends in fine sediment quantities (Figure 6). 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 and that those where USP was observed, had comparatively smaller infiltrating particles (Appendix D).

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 (Appendix D). In comparison, the average framework D_{50} for chalk stream gravel beds investigated in this study was 19.67 mm (Table 2), including several frameworks with a D_{50} of >25 mm. There was, however, a greater representation of infiltrating particle sizes in published experiments, ranging from 0.02 to 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

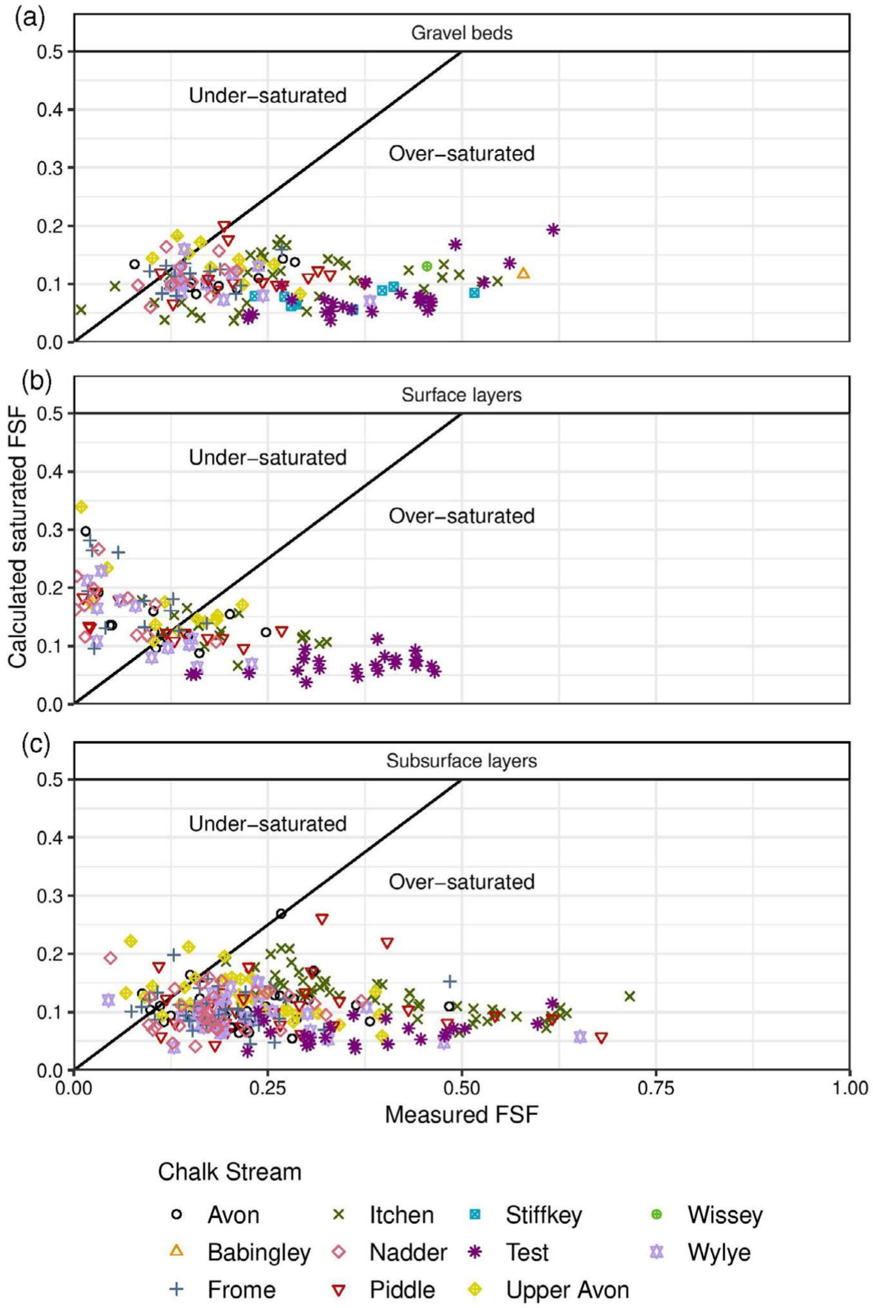

FIGURE 4 Comparison of calculated and measured FSF (Equation 1) in the investigated chalk stream gravel beds in (a) overall deposits (0–40 cm), (b) surface layers (0–10/15 cm) and (c) subsurface layers (10/15–40 cm). The equilibrium line represents a critical threshold of saturation, with gravel beds 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. [Color figure can be viewed at wileyonlinelibrary.com]

identified in chalk stream gravel beds were mostly poorly sorted to very poorly sorted, indicating high variation in the grain sizes present.

4 | DISCUSSION

Excessive fine sediment quantities can alter the natural functioning of freshwater systems, leading to detrimental impacts as observed internationally (e.g., Bašić et al., 2019; Bo et al., 2007; Robertson et al., 2006; Rosewarne et al., 2014; Sear et al., 2016). Chalk stream gravel beds often have higher proportions of fine sediment compared with other types of gravel-bed rivers (Acornley & Sear, 1999; Collins & Walling, 2007; 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). However, current approaches to fine sediment management and targets have failed to address fundamental issues specific to the chalk stream fine sediment problem (Mondon et al., 2021). 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.

4.1 | 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 bi-model

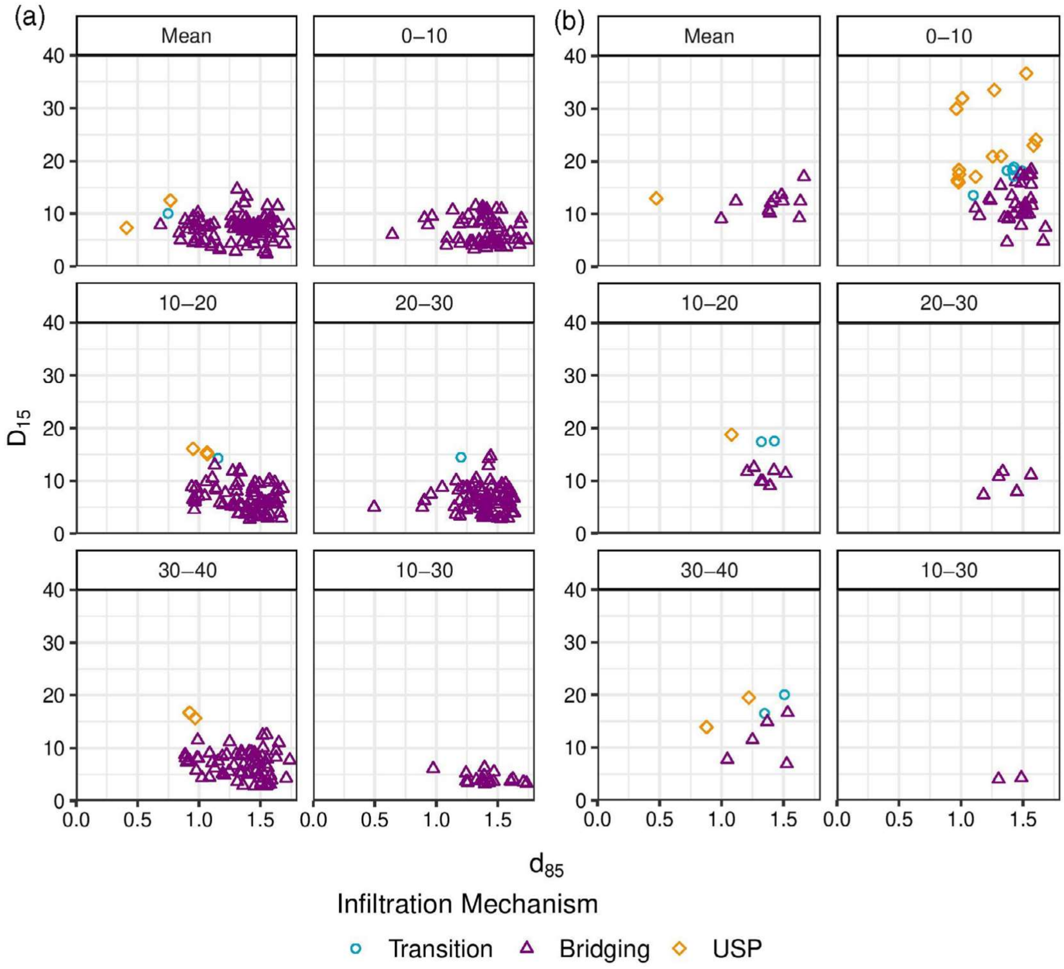

FIGURE 5 Occurrence of infiltration mechanisms in the investigated chalk stream gravel beds based on Equation (2), plotted by infiltrating fines d_{85} (excluding silt and clay-sized sediment, <62 μm) and framework gravel D_{15}, by bed layers and mean deposits for (a) over-saturated beds and (b) under-saturated beds. Points are grouped by infiltration mechanism. [Color figure can be viewed at wileyonlinelibrary.com]

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 3). For example, fine sediments accounted for 11.6% in highly flashy upland systems with low base flow indexes (Carling & Reader, 1982), 8.9% in the surface 20 cm of the River Exe, SW England (Lambert & 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 (0–10 cm) and deepest 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 (17%; Table 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 flume studies used to determine numerical models describing infiltration mechanisms (Appendix D), do not represent the natural conditions observed in chalk streams. In the determination of numerical models, few experiments (e.g., three of the 10 experimental runs used by Wooster et al. (2008)), used either 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 distributions, limited grain sizes, very distinctive fractions representing gravel and fines and often only considered the sand-sized fine sediment fraction (e.g., Dudill et al., 2017; Gibson et al., 2011; Kuhnle et al., 2013). Furthermore, the experimental gravel beds were often <10 cm deep (Appendix D), i.e., shallower than the 30–40 cm deep samples from chalk streams. We conclude that the published ex situ flume experiments reviewed in the present study are not representative of the GSDs typically found in natural chalk streams. Subsequently, models determined by these experiments have

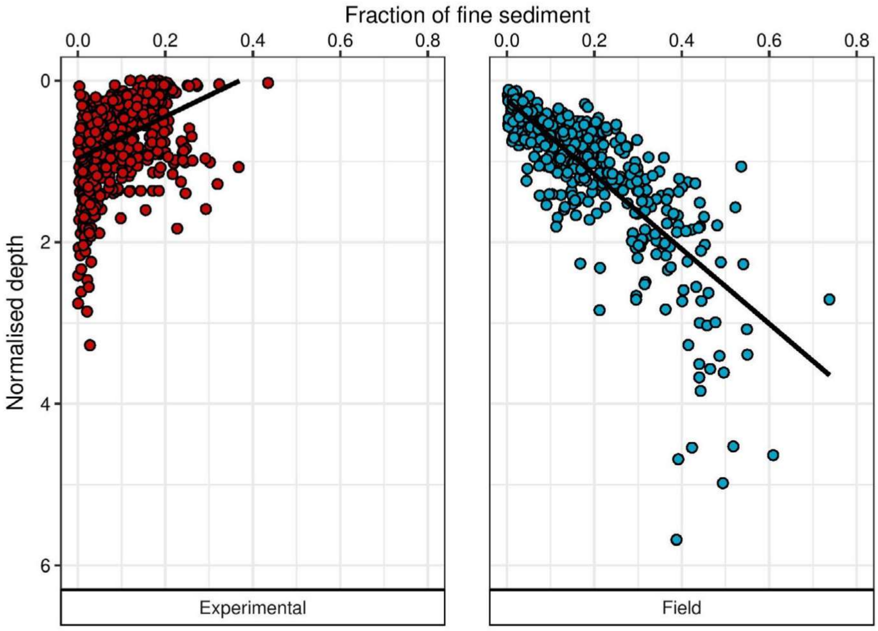

FIGURE 6 Vertical distributions of fine sediment quantity in the investigated chalk stream gravel beds (denoted by field data), compared with the results of fine sediment infiltration and accumulation in immobile gravel bed flume experiments (denoted by experimental data), where data on fine sediment accumulation was available (Wooster et al., 2008; Gibson et al., 2009, 2010, 2011; Huston & Fox, 2015; Herrero & Berni, 2016; Núñez-González, 2016, Appendix D). Depths of both the field and experimental beds have been normalised by the bulk D_{50} of each deposit, allowing for comparability between different depth profiles used in the original investigations. [Color figure can be viewed at wileyonlinelibrary.com]

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.

4.2 | Ecological suitability of gravel beds

Elevated fine sediment quantities have been extensively demonstrated to affect detrimentally aquatic organisms, and thresholds determined. For example, Heywood and Walling (2007) found that Atlantic salmon (*S. salar*) egg mortality was 100% when fine sediment quantities exceeded 14% of the total bed weight. Similarly, Greig, Sear, and Carling (2005) reported 91.3% mortality of Atlantic Salmon (*S. salar*) eggs when the proportion of fine sediment was 10% of the bed weight. Of the chalk stream gravel beds investigated in this study, 78% exceeded the 14% threshold (Heywood & Walling, 2007) and 95% exceeded the 10% threshold (Greig, Sear, & Carling, 2005). 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 Barbel (*Barbus barbus*) 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., 2005). Neglecting the silt and clay fraction could potentially explain the observed lower mortality, despite higher fine sediment quantity, in the case of Barbel (Bašić et al., 2019). Other species present in chalk streams have been identified as intolerant to excessive fine sediment, including, Ephemeroptera (*Baetis rhodani*) (Larsen & Ormerod, 2010; Wood et al., 2005), Isopoda (*Asellus aquaticus*) (Wood et al., 2005), mayfly (Ephemeroptera) eggs (*Serratella ignita*) (Everall et al., 2018), white clawed crayfish (*Austropotamobius pallipes*) (Rosewarne et al., 2014) and Brown trout (*S. trutta*) (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's of chalk stream gravel beds are the most ecologically sensitive to elevated fine sediment. Higher macroinvertebrate species abundance and diversity have been found in the benthic (0–5 cm) zone than in the hyporheic zone (>20 cm) in many chalk streams (Bunting et al., 2021; Davy-Bowker et al., 2006; Dunscombe et al., 2018; Stubbington et al., 2015). In addition, lithophilic fish species spawn in the surface 0–10/20 cm of chalk stream gravel beds, including Brown trout (*S. trutta*) (Acornley & Sear, 1999; Louhi et al., 2008; Milan et al., 2000), Barbel (*B. barbus*), Grayling (*Thymallus thymallus*) (Fabricus and Gustafsson, 1955; Gonzci, 1989), River lamprey (*Lampetra fluviatilis*) and Brook lamprey (*Lampetra planeri*) (Maitland, 2003; Silva et al., 2015). Atlantic salmon (*S. salar*) have been found to spawn up to 30 cm deep (Collins et al., 2014; DeVries, 2012; Milan et al., 2000). When considering the surface layers (0–10 cm) of the investigated chalk beds, those exceeding the fine sediment thresholds proposed by Heywood and Walling (2007) and Greig et al. (2005), were 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 & Carling, 1989). Consequently, future management and fine sediment targets should ideally focus on the improvement of this near-surface (depth < 10 cm) zone of chalk stream gravel beds.

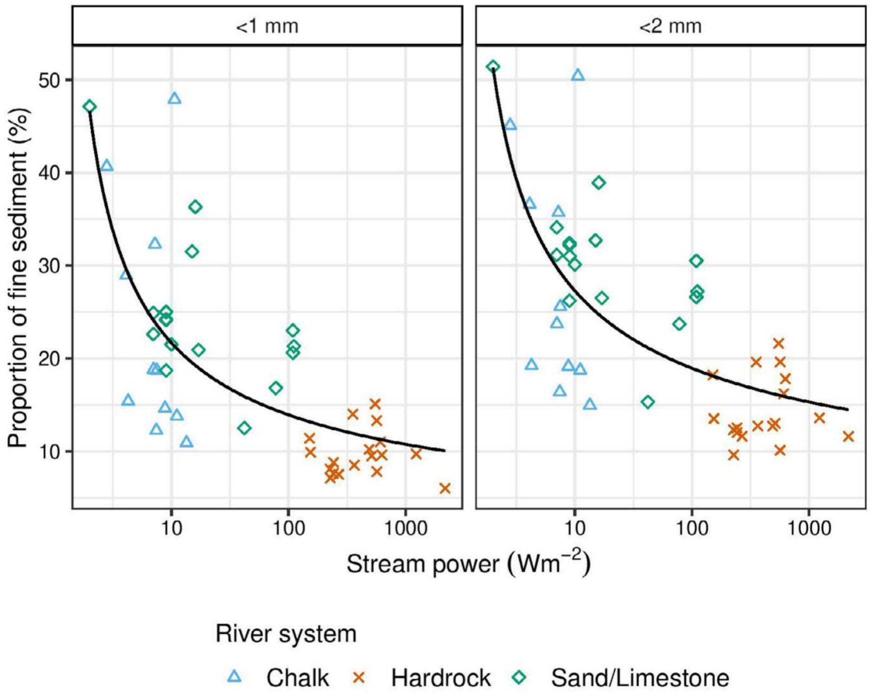

FIGURE 7 Average quantities of fine sediment (<1 and <2 mm) within the riverbeds of chalk streams and other gravel-bed river systems (Milan et al., 2000), compared with system stream power. Points are grouped by river system type. [Color figure can be viewed at wileyonlinelibrary.com]

4.3 | Causes of excessive fine sediment

Regardless of 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 functions. Fine sediment quantities in gravel beds have been shown to relate to a system's stream power (McKenzie et al., 2022; Naden et al., 2016; Sear et al., 2008). 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 C). Comparison between chalk streams and other gravel-bed systems in the United Kingdom (Figure 7) further 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 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.

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 Itchen, on average, has higher proportions of fine sediment (27.71% and 19.12%, respectively), indicating other factors. A proposed gravel bed sediment budget separates the controlling factors of fine sediment accumulation in chalk streams into four distinct overarching mechanisms (Mondon et al., 2021). 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 high 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 & Walling, 2007; 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 C). 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 & 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.

4.4 | Implications for sediment management

It is evident that both the 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 system's 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 slopes, which cannot be altered sufficiently to make substantial differences to specific stream power. Increases in chalk stream discharges are also not readily achievable, although further reductions can potentially be managed by restricting abstraction from the chalk aquifers (Soley et al., 2012). It is however worth noting that although abstraction from chalk aquifers can be restricted through licensing, it will persist for farming and potable supplies and thus, continue to influence flow conditions in chalk streams. Therefore, only the channel width of chalk streams can be efficiently altered with practical, readily available and cost-effective restoration and management techniques.

However, for chalk streams to have stream powers similar to gravel-bed systems where fine sediment quantities are consistently low (Figure 7), 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, the installation of large wood to generate localised regions of higher velocity, management of in-channel macrophytes to generate threads of highvelocity flows, and removal of obstructions such as weirs (Gurnell et al., 2006; Gurnell & Bertoldi, 2022; Heppell et al., 2009; Lenders et al., 2016; Osei et al., 2015; Parker et al., 2017). 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 larval stage of River lamprey (*L. fluviatilis*) (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), are 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-important 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.

5 | 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 important surface of 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 highlighted the need to consider sources in the management of fine sediment. 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 observed natural conditions, 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.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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APPENDIX A: Wentworth scale

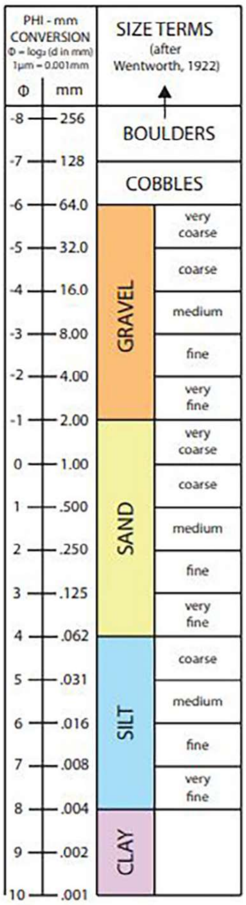

FIGURE A1 Wentworth scale of particle sizes (Bunte & Abt, 2001), separating particles in size classes increasing by a factor of two (e.g., 2–4, 4–8 and 8–16 mm). These size classes are grouped into six major particle-size categories: boulders, cobbles, gravel, sand, silt and clay (adapted from Wentworth, 1922). [Color figure can be viewed at wileyonlinelibrary.com]

APPENDIX B: Geometric method of moments

TABLE B1 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				

APPENDIX C: 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 of agricultural land.

TABLE C1 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

1.0
- 1.0

APPENDIX D: Sedimentary characteristics of experimental flume studies

TABLE D1 Sedimentary characteristics of experimental flume studies used to determine models describing the mechanisms of fine sediment infiltration and accumulation into immobile gravel beds.

		Bed sediment (mm)			Infiltrating sediment (mm)	
Experiment	Run	Depth	D_{gg}	σ_{gg}	D_{sg}	σ_{sg}
Einstein (1968)	1–5, 9–11		22.2	2.29	0.02	
	6–8		88.9			
Beschta and Jackson (1979)	1–18, 21	305	15.0	1.57	0.50	
	19, 20				0.20	
Carling (1984)	1–16	150	16.0	2.12	0.19	
	17–25	100			0.15	
Diplas and Parker (1992)	1–12		2.44	2.75	0.11	
	13–19				0.08	
Wooster et al. (2008)	Zone 1 & 10	120	7.20	1.87	0.35	1.24
	Zone 2		10.2	1.77		
	Zone 3		13.1	1.68		
	Zone 4		17.2	1.17		
	Zone 5		7.30	1.90		
	Zone 6		7.90	1.22		
	Zone 7		8.70	1.71		
	Zone 8		7.60	1.46		
	Zone 9		4.30	1.65		
Gibson et al. (2009)	IFS 1	100	7.10	1.37	0.43	1.70
	IFS 2				0.26	1.94
	IFS 3				0.21	1.55
	IFS 4				0.12	1.37
Gibson et al. (2010)	Zone 1	100	9.70	1.27	0.21	1.55
	Zone 2		7.20	1.39		
	Zone 3		6.00	1.19		
	Zone 4		5.30	1.24		
	Zone 6		3.70	1.25		
	Zone 8		2.90	1.10		
Gibson et al. (2011)	S1	100	7.70	1.41	0.65	1.58
	S2				0.36	1.66
	S3		9.70	1.27		
Kuhnle et al. (2013)	1–30		35.0	1.15	0.30	
Dudill et al. (2017)	Run 1		5.00		0.70	
	Run 2				0.90	
	Run 3				1.50	
	Run 4				2.00	
	Run 5				3.00	
	Run 6				4.00	

APPENDIX E: Surface vs. subsurface GSDs

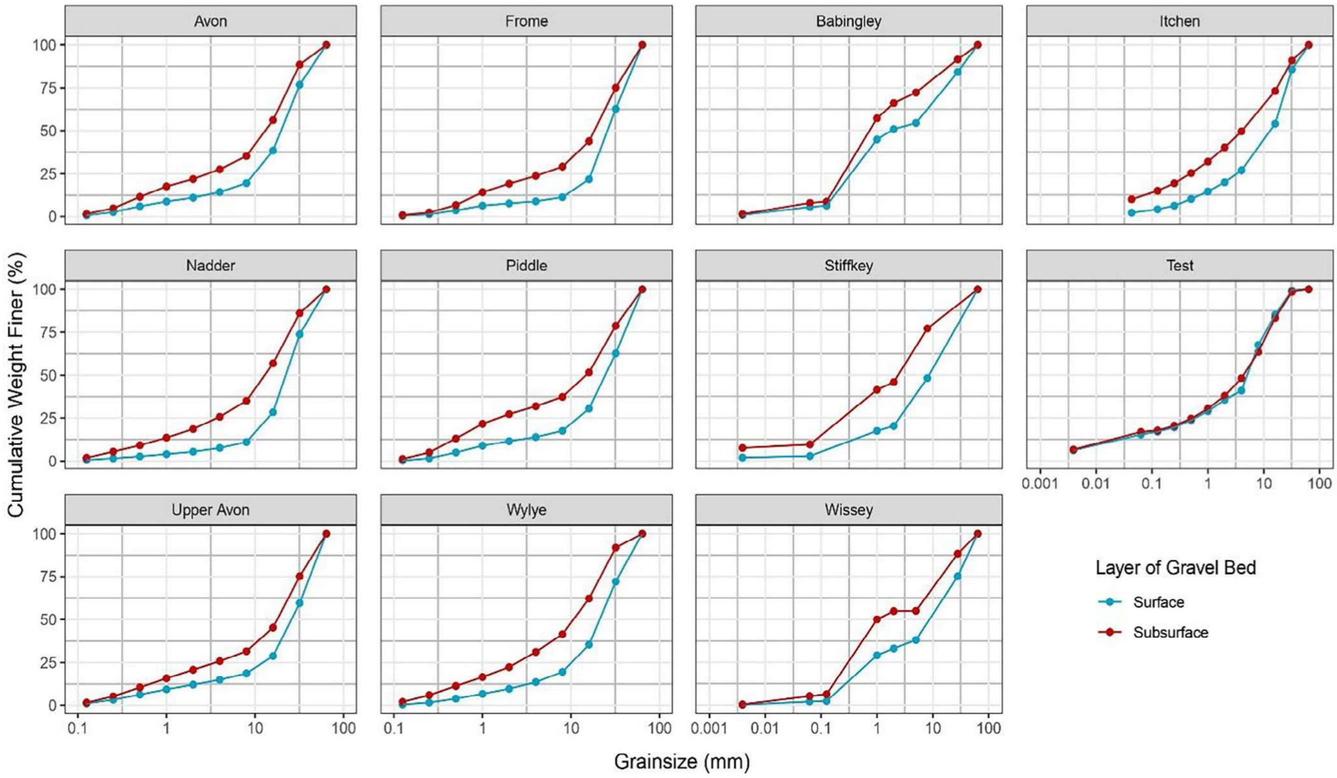

FIGURE E1 Mean GSD curves for each of the chalk stream gravel beds investigated, coloured by surface (0–10 cm) and subsurface (10–40 cm) layers, as depicted in the figure legend. The Rivers Babingley and Wissey are separated by surface (0–15 cm) and subsurface (15–30 cm) layers based on data reported in the original investigation. [Color figure can be viewed at wileyonlinelibrary.com]