

# The impact of plants on fine sediment storage within the active channels of gravel-bed rivers: A preliminary assessment

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## Abstract

The role of aquatic and riparian vegetation in driving morphodynamics of rivers is being increasingly recognized across all river types. Here, we focus on gravel-bed rivers, where the ability of vegetation to influence morphodynamics depends upon the retention and stabilization of predominantly sand and finer sediments to build landforms within the active channel. One aspect of such interactions among vegetation, river flows and transported sediments that has received little research attention is their contribution to within-channel storage of fine sediment as a potentially important component of the fine sediment budget of river reaches and catchments. In this article, we assemble some preliminary estimates of the fine sediments retained by vegetation across the active channels of four gravel-bed rivers (12 river reaches) representing a wide range in river planform (near-straight, meandering, braided), width (6–800 m), gradient (0.0008–0.004) and  $Q_2$  flood (2–1100 m<sup>3</sup> s<sup>-1</sup>), and including reaches where submerged and emergent macrophytes and riparian trees and shrubs act as physical ecosystem engineers. Our results indicate that vegetation can retain sizeable quantities of fine sediment, ranging from 480 to >3000 kg m<sup>-2</sup> in emergent vegetation-engineered landforms, equivalent to 20–1000 kg m<sup>-2</sup> when averaged across the entire active channel area. Vegetation retains virtually all the fine sediments stored on the bed surface of these active channels, increasing from 78% in the lowest energy to 100% in the highest energy river reaches investigated, with major differences in the locations of these vegetated fine sediment stores according to river planform style and unit stream power. These preliminary estimates suggest that fine sediment retention and storage by vegetation is potentially an important component of within-channel sediment budgets as well as contributing to the hydrological, geomorphological and ecological functioning of rivers.

## KEYWORDS

active river channel, aquatic vegetation, fine sediment storage, riparian vegetation, sediment budgets

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## 1 | INTRODUCTION

Fluxes of water and sediment drive river system morphodynamics with flux changes affecting the size, style, sedimentary structure and mobility of fluvial systems. Delivery, transfer and retention of sediment within fluvial systems has been increasingly impacted by human activities through the Holocene (Hoffmann et al., 2010), culminating in the dramatic impacts observed in the Anthropocene (Owens, 2020). Resultant river channel morphological and sedimentary changes can affect hydrological and ecological functioning of river environments, particularly when flux changes introduce contaminated sediments (Ballantine et al., 2009; van der Perk & Jetten, 2006; Walling & Owens, 2003). To advance scientific understanding and support management decision making, it is important to try to quantify sediment delivery-transfer-retention across space from catchment to reach scales and over time from events to decades (Frings & Ten Brinke, 2018; Jordan, 2006; Walling & Collins, 2008).

One concept that has been used to support such quantification is the sediment budget. Sediment budgets conceptualize and quantify relationships among inputs, outputs and storages of sediment within a particular spatial context and period of time. Once the cascade of inputs, stores, outputs are conceptualized, as many as possible are quantified for the specified time period using a variety of methods (Brown et al., 2009). Early attempts focused on field-based process measurements and sedimentological-volumetric measurements of sediment stores within a context of geomorphological interpretations of landscape features (Duijsings, 1987; Phillips, 1991; Slaymaker, 1993; Trimble, 1983, 1993). Many studies have used measurements from human-made stores of known age (e.g. lakes and ponds) to compute budget components and reveal human impacts (Foster et al., 2021). Laboratory analyses of sediment samples have provided an indirect means of estimating proportional source contributions by 'fingerprinting' sediment characteristics (Pulley et al., 2017; Walling et al., 1998, 2006), with further advances extending the spatial and temporal scales of quantification using information from aerial and satellite imagery, lidar data and modelling (Bizzi et al., 2021; Khan et al., 2021; Piégay et al., 2020).

Sediment budget research has led to major advances in our understanding of both natural and human-influenced sediment sources, storages and transfers across river landscapes. However, because some elements are difficult to measure, these unknowns are frequently estimated by mass balance computations (Slaymaker, 2003), leading some authors to raise cautions regarding the usefulness of sediment budget calculations (Kondolf & Matthews, 1991; Parsons, 2012). Inherent errors in budget calculations are particularly large when simple mass balance calculations are employed but sizeable errors are likely to be present in all sediment budget computations, suggesting the importance of directly estimating as many budget components as possible.

One component that is particularly challenging to calculate is the storage of sediment within river channels (Harper et al., 2017). Estimation of in-channel storage of sediments, particularly fine sediments, is important not only to improve the accuracy of sediment budget

calculations but because fine sediment affects the structure and function of river ecosystems (Mondon et al., 2021). In gravel-bed rivers, fine sediments can reduce pore-water fluxes and hyporeic exchanges through the river bed (Collins & Walling, 2007a) and in extreme cases can completely smother the gravel bed, affecting river water temperature, biogeochemical process, and organisms including fish, macroinvertebrates and macrophytes (Heywood & Walling, 2007; Jones, Collins, et al., 2012; Jones, Murphy, et al., 2012; Pulley et al., 2019). As a result, this estimation challenge has been pursued by developing methods to directly quantify fine sediments retained in the bed of gravel bed river channels (Ballantine et al., 2009; Collins & Walling, 2007a; Harper et al., 2017; Lambert & Walling, 1988; Marttila & Kløve, 2014).

Over the last two decades, researchers have increasingly considered the role of aquatic and riparian vegetation in trapping finer sediments, building landforms and influencing the morphodynamics of river channels (Bertoldi et al., 2011; Corenblit et al., 2007, 2009; Gurnell, 2014; Gurnell et al., 2012, 2016). Laboratory experiments have demonstrated that vegetation retains sediment and have explored how this process occurs. At the scale of a single vegetated patch, experiments have demonstrated relationships among vegetation density, flow characteristics and downstream deposition of fine sediments. Sediment deposition is induced by a decrease in average flow velocity (where vegetation acts as an obstacle) and a decrease in turbulence velocity (Kim et al., 2015; Liu & Nepf, 2016; Zong & Nepf, 2010). Experiments have also shown that different types of vegetation influence the amount and location of deposited sediments. Significant differences have been highlighted between emergent and submerged flexible vegetation; vegetation with or without flexible leaves; and where a vegetated patch is limited in width or spans the whole water width (Hu et al., 2018; Ortiz et al., 2013). Furthermore, Elliott et al. (2019) have confirmed that submergence is a critical parameter affecting the amount and longitudinal spread of deposition, with low submergence rates promoting longitudinal patch expansion that further reinforces the effect of vegetation. Sediment trapping has also been quantified in the field when retained by large wood (Hart, 2002; May & Gresswell, 2003; Parker et al., 2017; Ryan et al., 2014; Sutfin et al., 2021; Welling et al., 2021), although often focusing on total sediment retention rather than just fine sediment retention. However, there have been few attempts to quantify fine sediment retention by living vegetation within river channels. The role of aquatic macrophytes has been recently assessed in lowland streams (Drexler et al., 2021; Larsen, 2019; O'Briain et al., 2022), in relation to gully infilling (Zierholz et al., 2001) and in tidal environments (Bouma et al., 2007) but little is known about sediment retention in larger rivers, where riparian vegetation is likely to be the vegetation type interacting with fluvial processes (Gurnell et al., 2012). This lack of quantification is important because the retention of fine sediment by vegetation incorporates sediment into intermediate landform stores within the active channel and riparian zone, affecting channel form and dynamics and reducing the amount of fine sediment that might otherwise infiltrate or smother the river bed.

**TABLE 1** The studied rivers—reach locations (approximate mid-points) and planform styles

River	Reach	Reach planform	Latitude	Longitude
Blackwater, England	A	Single thread, realigned	51.2664	−0.7316
	B	Single thread, near-straight	51.2878	−0.7364
	C	Single thread, realigned	51.3208	−0.7636
Frome, England	A	Single thread, near-straight	50.7603	−2.5510
	B	Single thread, near-straight	50.7600	−2.5510
	C	Single thread, near-straight	50.7511	−2.5288
	D	Single thread, near-straight	50.7507	−2.5275
	E	Single thread, sinuous	50.7507	−2.5267
Isère, France	A	Single thread, realigned, embanked	45.4130	6.0000
Lower Tagliamento, Italy	A	Single thread, meandering	45.8150	12.9840
Middle Tagliamento, Italy	A	Multi-thread, bar braided	46.2320	13.0410
	B	Multi-thread, island braided	46.2040	12.9830

**TABLE 2** Study reach characteristics

River	Reach	Active width (m)	Reach length (m)	Main channel gradient (m m <sup>−1</sup> )	Q <sub>2</sub> annual maximum daily flow (m <sup>3</sup> s <sup>−1</sup> )	Total stream power at Q <sub>2</sub> (W m <sup>−1</sup> )	Unit stream power at Q <sub>2</sub> (W m <sup>−1</sup> )	Y (m)
Blackwater, England	A	6.3	46	0.0011 <sup>a</sup>	1.74	18.8	2.98	0.44
	B	8.7	34	0.0009 <sup>a</sup>	2.36	20.8	2.39	0.46
	C	8.2	81	0.0008 <sup>a</sup>	3.02	23.7	2.79	0.56
Frome, England	A	8.7	60	0.0025 <sup>a</sup>	6.41	157	18.1	0.61
	B	9.6	85	0.0025 <sup>a</sup>	6.41	157	16.4	0.58
	C	9.9	110	0.0026 <sup>a</sup>	6.41	163	16.5	0.56
	D	10.5	85	0.0026 <sup>a</sup>	6.41	163	15.6	0.54
	E	10.5	127	0.0026 <sup>a</sup>	6.41	163	15.6	–
Isère, France	A	100	4600	0.0014	360 <sup>b</sup>	4940	49.4	1.89
Lower Tagliamento, Italy	A	110	800	0.0009	1100 <sup>c</sup>	9710	88.2	3.98
Middle Tagliamento, Italy	A	800	1500	0.0040	1100 <sup>c</sup>	43 200	53.9	0.77
	B	580	1300	0.0037	1100 <sup>c</sup>	39 900	68.8	0.96

<sup>a</sup>Gradients calculated for extended reaches, several km long, within which the studied reaches were located.

<sup>b</sup>From Serlet et al. (2018).

<sup>c</sup>From flow stage data from 2001 to 2021, converted to discharge by means of unofficial estimated rating curves developed on the basis of unpublished velocity measurements made by the authors.

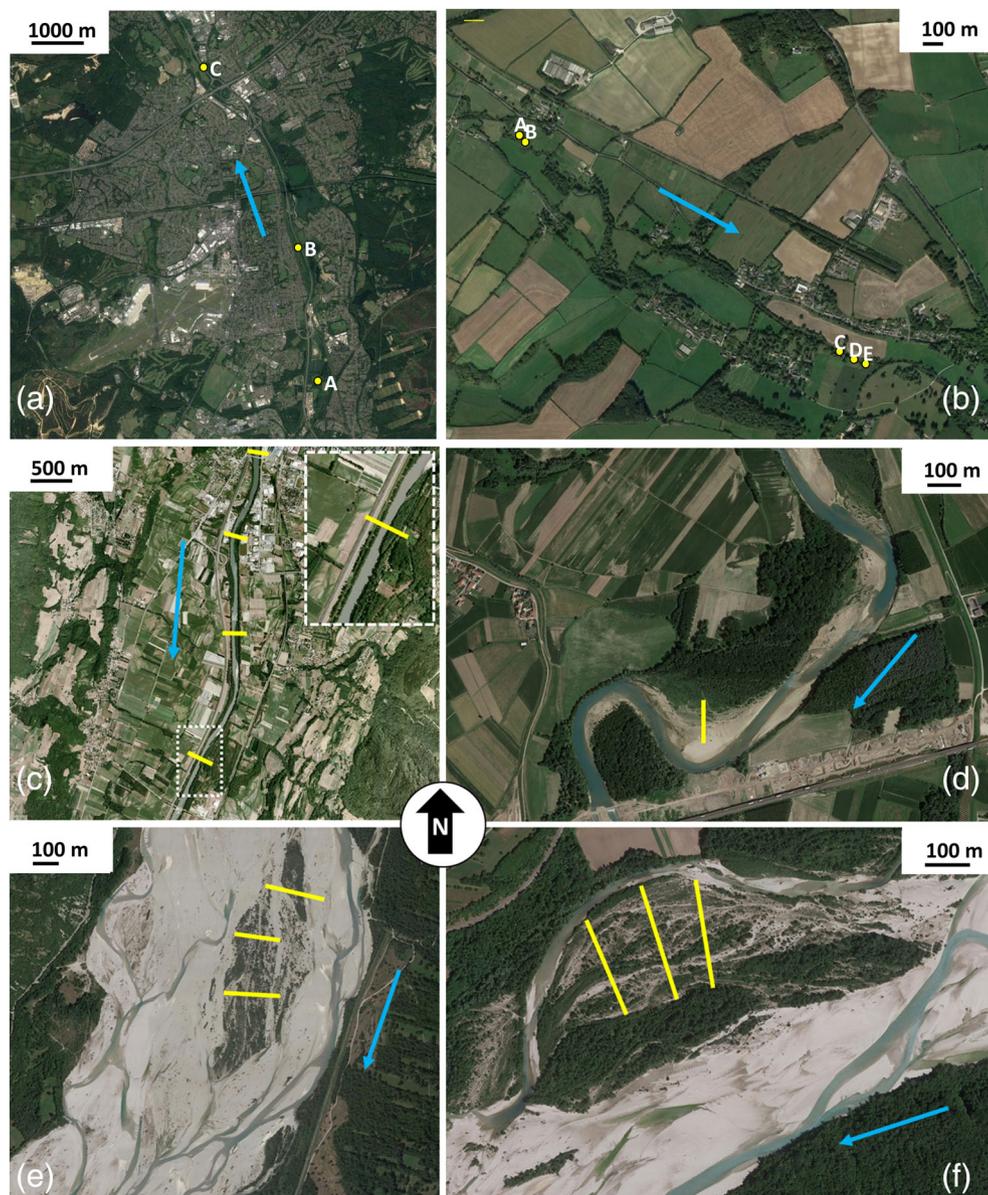
Our research integrates data sets collected on different gravel-bed rivers in an attempt to estimate the proportion of fine sediment that can be retained by vegetation within the active channel. We use the term fine sediment to refer to the sand and finer (<2 mm) particle size fraction. We hypothesise that in-channel retention of fine sediment on the channel bed by vegetation may constitute a significant fine sediment store and we focus on two main research questions:

1. Are there differences in the proportions of fine sediment retained by vegetation on the beds of active river channels of different size, gradient and planform?
2. Are there differences in the locations of fine sediment retained by vegetation within active river channels of different size, gradient and planform?

## 2 | DATA AND METHODS

### 2.1 | Study sites

We analyse data from 12 reaches of four gravel-bed rivers of different size and planform (Tables 1 and 2, Figure 1), focusing on sand and finer sediment (<2 mm) rather than the silt and finer (<0.0625 mm) size range often described as ‘fine sediment’. The data comes from archive field surveys not specifically collected for the present purpose, complemented by data from aerial images and airborne lidar and includes some new field surveys along the Tagliamento river, Italy (Figure 1d–f). This mix reflects both the original purposes of data collection and the types of survey that are feasible across such widely varying river channel sizes.



**FIGURE 1** The studied river reaches. (a) Blackwater – Locations of reaches A, B and C; (b) Frome – Locations of reaches A, B, C, D, E; (c) Isère reach (inset enlargement illustrates the embanked channel and alternate vegetated bars); (d) Lower Tagliamento reach; (e) Middle Tagliamento reach A; (f) Middle Tagliamento reach B. The yellow lines in (c), (d), (e), (f) locate the studied transects. All images extracted from Google Earth: (a) (b) and (c) image Landsat/Copernicus; (d) (e) and (f) image @ 2021 Maxar Technologies

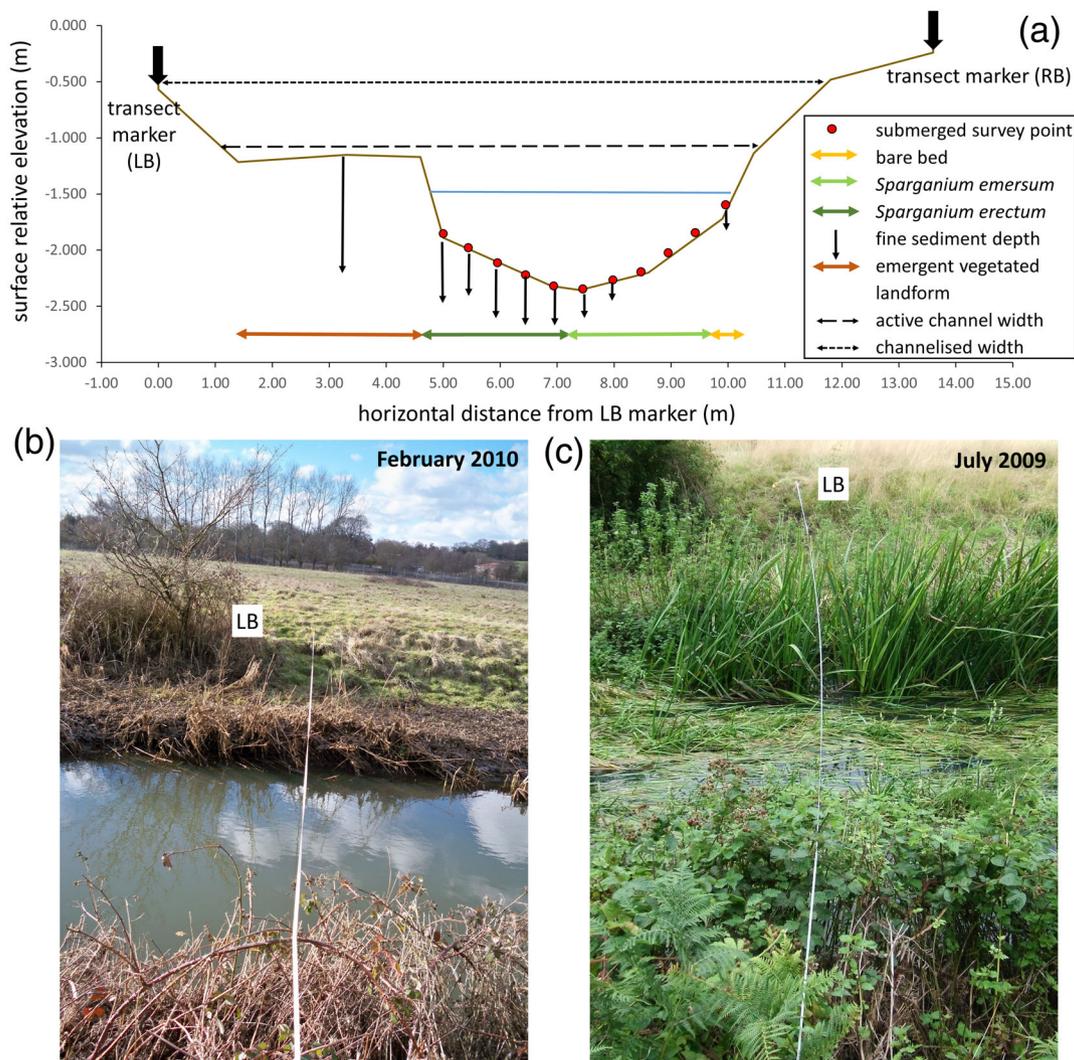
## 2.2 | Data

Our approach to quantifying fine sediment retention focuses on river transects within specific reaches (Tables 1 and 2). We used a mix of inserting graduated, metal rods; excavating sediments; or viewing natural exposures to estimate the depth of fine sediment from the surface to underlying gravels. We couple these point measurements with topographic surveys of each studied transect and, for the Tagliamento reaches, airborne lidar data to provide a broader aerial coverage. We combine our estimates of superficial fine sediment depth with vegetation cover (bare sediment; submerged macrophytes; emergent macrophytes; riparian vegetation) to estimate sediment depths and depth changes over time associated with each cover type. Reflecting the large differences in river width and depth, the detailed methods used to quantify fine sediment vary among the study sites.

### 2.2.1 | Blackwater

Twenty-seven cross-river transects were investigated in three straight reaches (10 transects in reaches A and C, 7 in reach B). The measurement design along each transect is shown schematically in Figure 2. The positions and cross profiles of the transects were surveyed on one occasion using a combination of DGPS and a survey level. Bed cover types (bare, submerged and emergent vegetation) were recorded at peak biomass in July 2009 at 0.5 m intervals across the submerged bed (note that in the winter there is no above-ground macrophyte biomass). Emergent macrophytes were almost entirely *Sparganium erectum* and the submerged macrophytes were almost entirely *Sparganium emersum*.

The depth of superficial fine sediment was determined at the same transect locations as bed cover types on two occasions (early Spring 2009 and 2010) to determine the depth distribution of fine



**FIGURE 2** Transect-based survey design employed on the Rivers Blackwater and Frome. (a) A transect locating equally spaced submerged survey points where cover types (bare bed, submerged macrophytes (e.g. *Sparganium emersum*), emergent macrophytes (e.g. *Sparganium erectum*) and depth through finer sediments to the underlying gravel were recorded. A vegetated landform (bench) within the active channel and location of finer sediment depth measurement. (b) and (c) photographs of the transect depicted in (a) illustrating the absence of in-channel above-ground vegetation biomass in late winter (b) and above-ground biomass distribution in mid-summer (c). The river channel was created when the river was diverted to make way for road construction. The channelized width and the currently active channel width are both indicated

sediment and any changes over a year. Fine sediment depth in vegetated emergent landforms within the active channel was determined in Spring 2009 from a combination of surveyed cross profiles coupled with occasional measurements of fine sediment depth to underlying gravel.

## 2.2.2 | Frome

Ten cross-river transects were investigated in each of four straight reaches. The survey design was almost identical to that for the River Blackwater (Figure 2). The main differences were that measurements were made at 1 m intervals across the submerged part of each transect, superficial bed sediment depths were measured in March and August 2004, and bed cover types were recorded in August 2004.

Emergent macrophytes were almost entirely *S. erectum* and submerged macrophytes were almost entirely *Ranunculus* spp.

In order to link the distribution of macrophytes to the development of emergent vegetated landforms, a spatial analysis of the changing position of the channel water margins and emergent macrophyte stands used evidence from Google Earth aerial images captured in the summers of 2005, 2010, 2017 and 2020. A sinuous reach (E) was selected for this analysis, which overlapped with the downstream end of reach D.

## 2.2.3 | Isère

Historical surveys (1989, 1999, 2015) of four transects within a 4.6 km reach were analysed to estimate changes in the depths of

superficial fine sediment in the cross-profiles associated with vegetated (mainly riparian trees, dominated by *Salix alba*) and unvegetated areas. Field studies of this reach have established that the main areas for fine sediment retention in the reach are within alternate vegetated bars where fine sediments can be over 3 m deep, while the inundated area has a gravel bed and supports negligible vegetation or superficial fine sediment (Serlet et al., 2018). Therefore, the sediment retention computations relied upon cross-profile geometry and the extent of the vegetated area across that geometry.

## 2.2.4 | Lower Tagliamento

A single transect across the inner bank of a meander bend was surveyed in 2021 by DGPS, recording topography and vegetation cover (*Populus nigra* dominated woodland) at the same location as a previous survey in 2014 (Zen et al., 2017). This allowed topographic and vegetation changes to be computed over a 7 year period. During the 2021 survey, the depth of fine sediment above underlying gravels was measured at a few points along the transect. To accommodate the impact of channel movements into the computations, changes in channel position were extracted from Google Earth images and vegetation biomass was estimated from satellite data (Planet collection, 3 m spatial resolution, RGB and infrared bands) using the NDVI index.

## 2.2.5 | Middle Tagliamento

Six transects were surveyed by DGPS (3 in reach A during 2022, 3 in reach B during 2021) across the vegetated part of the active channel bed. This vegetated area marks the full extent of fine sediment accumulation on the gravel bed of the active channel. In reach B (Figure 1f), the vegetated area to the south of the surveyed transects was excluded from analysis, because it is an established island whose surface elevation has not changed significantly for at least 15 years and so it is not part of the currently active channel. Topographic data from these surveys was combined with 2022 field measurements of fine sediment depth to the underlying gravel and surface elevation and vegetation height (*P. nigra*-dominated shrub and woodland cover) for the same transects extracted from airborne lidar surveys (2010, 2013, see Bertoldi & Gurnell, 2020). Additional information on vegetation biomass was extracted from satellite data (Planet collection, 3 m spatial resolution, RGB and infrared bands) by applying the NDVI index.

## 2.3 | Data analysis

Reflecting differences in the analysed data sets, we present estimates of fine sediment retention by vegetation in slightly different ways for each of the studied reaches. In each case we attempt to estimate the depths or volumes of fine sediment stored in submerged or emergent locations within the active channel, and the degree to which retained

sediment is associated with different cover types and has changed over specific time periods.

The selected reaches were characterized by the width of the active channel ( $W$  in m), the average longitudinal gradient ( $s$  in  $\text{m m}^{-1}$ ) and the 2 year return interval daily average discharge ( $Q_2$  in  $\text{m}^3 \text{s}^{-1}$ ) (Table 2). These parameters were used to compute total stream power, unit stream power and an average flow depth ( $Y$ ), considering a normal flow in an equivalent rectangular cross section, with a standard roughness coefficient (Manning's  $n$ ) of  $0.03 \text{ m}^{-1/3} \text{ s}^{-1}$ .

$$Y = \left( \frac{nQ_2}{W\sqrt{s}} \right)^{0.6}$$

$Y$  can be considered an intrinsic driver (and limit) for the fine sediment layer depth because we only consider sediment retention within the active channel. The computed quantities of fine sediment depth were normalized by dividing by  $Y$  to support comparisons between reaches in relation to their unit stream power.

We also converted estimates of sediment depth/volume to weight units in order to compare our results with those from other studies of fine sediment storage on river beds that use such units (typically  $\text{kg m}^{-2}$  or  $\text{g m}^{-2}$ ). To achieve this conversion we used the average density of rocks ( $2650 \text{ kg m}^{-3}$ ) combined with a porosity of 0.4, which is suitable for relatively fine sediments (Frings et al., 2011). While 0.4 is widely used as a porosity for relatively uniform sand deposits, we could have chosen values in the range 0.25–0.45, with lower values associated with more heterogeneous and coarser sediments (Román-Sierra et al., 2014; Seitz et al., 2018).

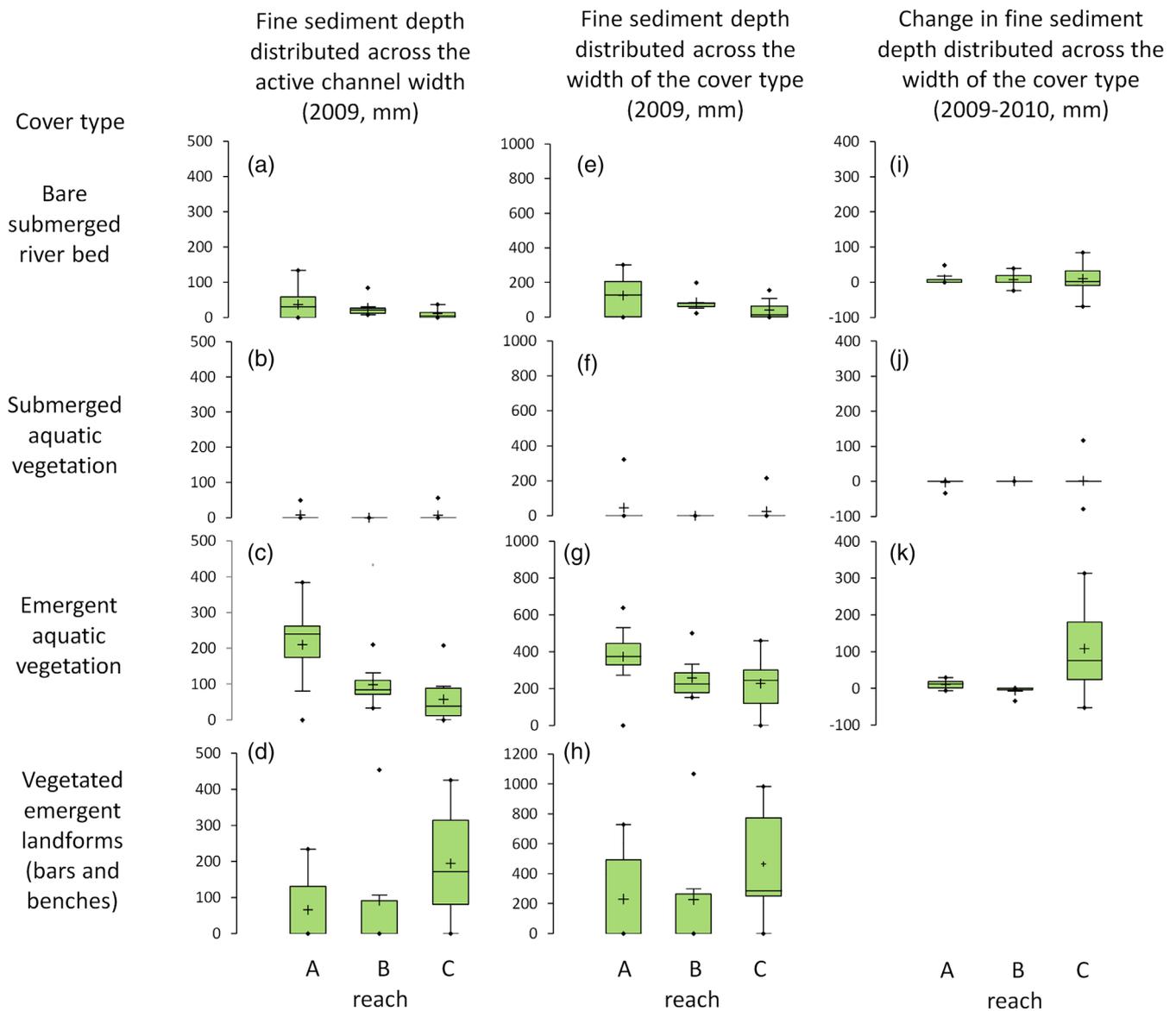
## 3 | RESULTS

### 3.1 | Blackwater

A summary of sediment-vegetation transect information collected in Blackwater reaches A, B, C is provided in Figure 3.

Distributing the quantity of sediment retained by each cover type across the width of the active channel, box and whisker plots (Figure 3a–d) identify the relative sediment storage importance of four in-channel cover types. Submerged aquatic vegetation (mainly *S. emersum*) retains near-zero fine sediment (A, C means: 0.7, 0.6 cm; no submerged vegetation in reach B). Small quantities of fine sediment are retained on the surface of the bare bed (A, B, C means: 3.7, 2.7, 1.1 cm). The largest depths are retained around emergent macrophytes (mainly *S. erectum*; A, B, C means: 21.0, 9.8, 5.7 cm) and within emergent vegetated landforms (A, B, C means: 6.6, 9.1, 19.4 cm). The relative importance of these two cover types for sediment retention varies between reaches, possibly reflecting a change in the mix of landform types from predominantly vegetated side-bars in reaches A and B to predominantly benches in C.

When the depth of sediment retained by each cover type is distributed across the area under each cover type, box and whisker plots reveal the relative roles of each cover type in retaining sediment



**FIGURE 3** River Blackwater. Box and whisker plots illustrating reach estimates (reaches A, B, C) of fine sediment depth for areas of bare bed (a, e, i), submerged macrophytes (b, f, j), emergent macrophytes (c, g, k), and vegetated emergent landforms (d, h). Fine sediment depths for each cover type measured in March 2009 and distributed across the entire active channel width (a, b, c, d) illustrate the relative contributions of the cover types in whole-channel fine sediment storage. Fine sediment depths for each cover type distributed across the average width occupied by each cover type (e, f, g, h) illustrate the local importance of each cover type for fine sediment retention. Changes in sediment depth (between March 2009 and February 2010) are also shown across the average width of each submerged cover type (i, j, k). The distribution of submerged/emergent vegetation and bare bed was recorded in July 2009. No change in sediment depth can be estimated for vegetated emergent landforms because the computation for this cover type incorporates information from the topographic cross-profiles which were only surveyed once

locally (Figure 3e–h, note the different scale on the vertical axis of h). Emergent vegetated landforms retain the largest depths (A, B, C means: 23.1, 22.8, 46.5 cm), followed by emergent macrophytes (A, B, C means: 37.4, 25.8, 22.8 cm), followed by bare bed (A, B, C means: 12.5, 8.4, 4.2 cm) with the shallowest depths associated with submerged macrophytes (A, C means: 4.4, 2.4 cm). Note that these reach means incorporate zeros for transects where the cover type is absent.

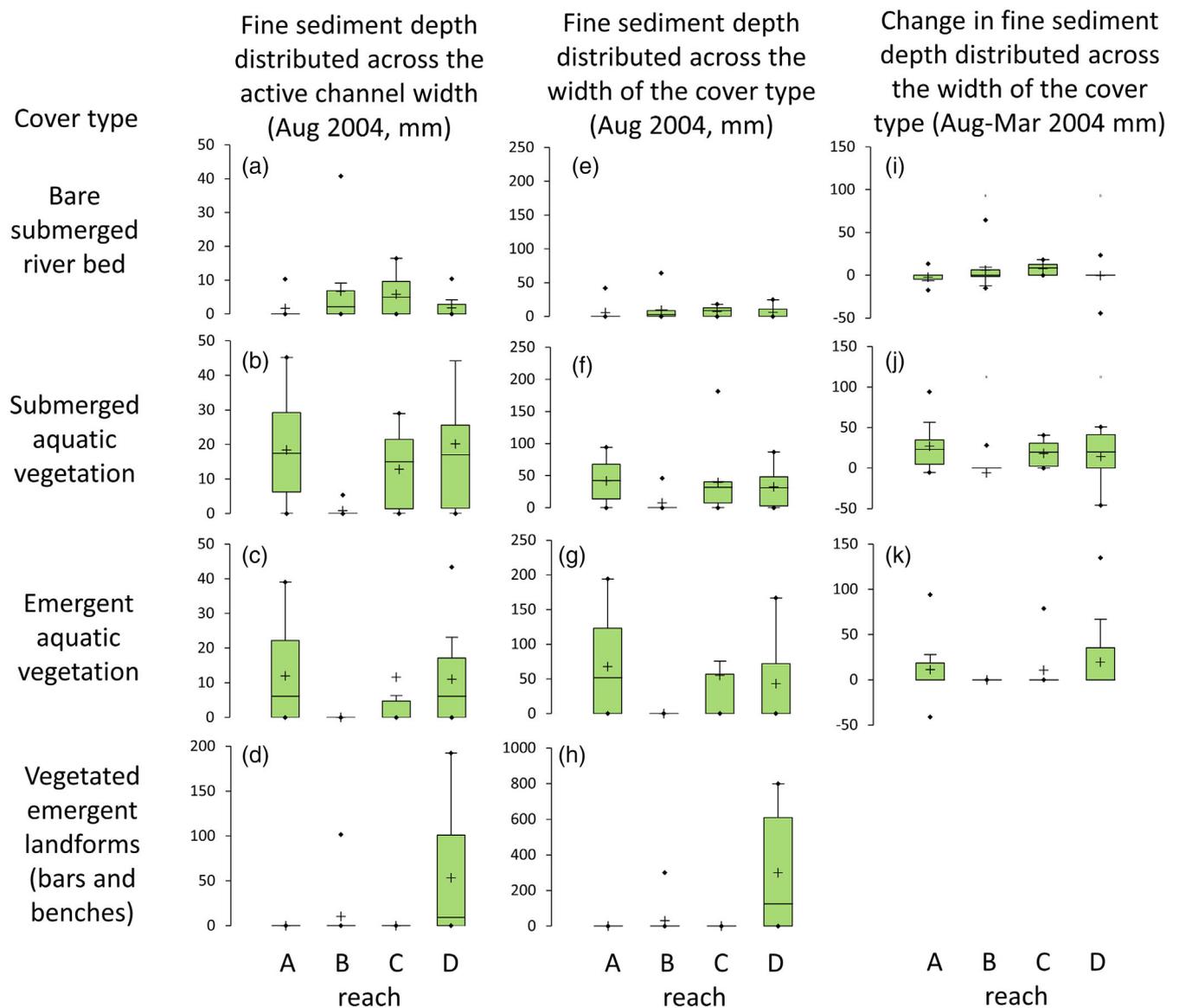
Changes over a year in the depth of fine sediment under each cover type (March 2009 to February 2010, Figure 3i–k) are largest under emergent macrophytes (A, B, C means: 1.2, –0.6, 10.8 cm),

followed by bare bed (A, B, C means: 0.8, 0.8, 1.0 cm), followed by submerged macrophytes (A, C means: –0.3, 0.2 cm).

### 3.2 | Frome

A summary of the sediment-vegetation transect information collected within four reaches of the Frome is provided in Figure 4.

Distributing the quantity of sediment retained by each cover type across the width of the active channel, box and whisker plots

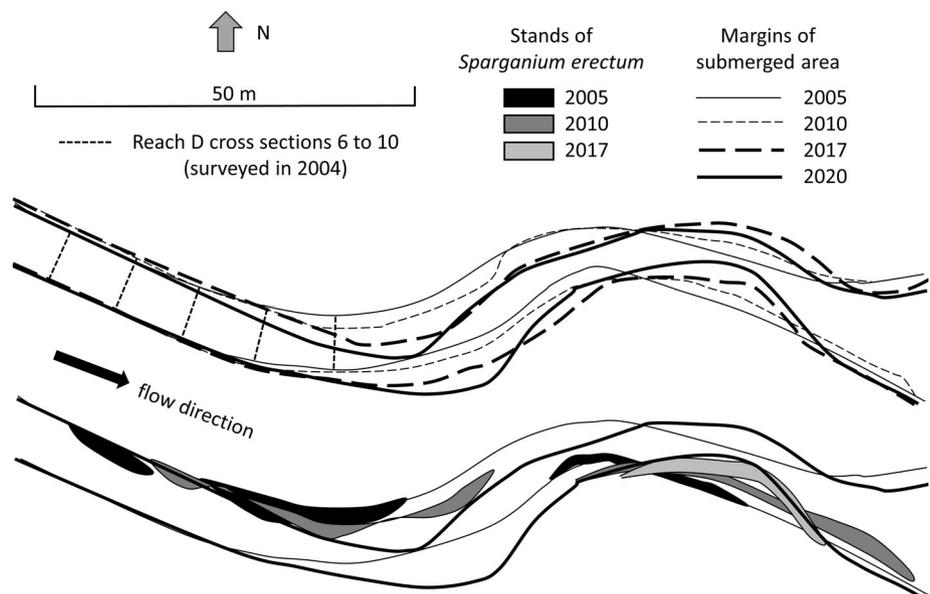


**FIGURE 4** River Frome. Box and whisker plots illustrating reach estimates (reaches A, B, C, D) of fine sediment depth for areas of bare bed (a, e, i), submerged macrophytes (b, f, j), emergent macrophytes (c, g, k), and vegetated emergent landforms (d, h). Fine sediment depths for each cover type (recorded in August 2004) and distributed across the entire active channel width (a, b, c, d) illustrate the relative contributions of the cover types in whole-channel fine sediment storage. The same fine sediment depths distributed across the average width occupied by each cover type (e, f, g, h) illustrate how local fine sediment retention varies with cover type. Changes in sediment depth (between March and August 2004) are also shown across the average width of each submerged cover type (i, j, k). The distribution of submerged/emergent vegetation and bare bed was recorded in August 2004. No change in sediment depth can be estimated for vegetated emergent landforms because the computation for this cover type incorporates topographic cross-profiles which were only surveyed once

(Figure 4a–d) identify the relative sediment storage importance of four in-channel cover types. Small quantities of fine sediment are retained on the surface of the bare bed (A, B, C, D means: 0.2, 0.7, 0.6, 0.2 cm). Submerged (mainly *Ranunculus* spp.; A, B, C, D means: 1.8, 0.1, 1.3, 2.0 cm) and emergent macrophytes (mainly *S. erectum*; none in reach B; A, C, D means: 1.2, 1.2, 1.1 cm) retain similar sediment quantities that exceed those of the bare bed. Emergent vegetated landforms, only present in reaches B and D, retained slightly more sediment than the aquatic plants (B, D means: 1.0, 5.3 cm).

When the observed fine sediment depths are distributed only across the bed area under the relevant cover type (Figure 4e–h, note the different scale on the vertical axis of h), emergent vegetated landforms retain the largest depths (B, D means: 3.0, 35.4 cm), followed by emergent macrophytes (A, C, D means: 6.8, 5.5, 4.3 cm), followed by submerged macrophytes (A, B, C, D means: 4.2, 0.7, 4.0, 3.3 cm), with the shallowest depths on areas of bare bed (A, B, C, D means: 0.6, 1.0, 0.8, 0.6 cm). Note that these reach means incorporate zeros for transects where the cover type is absent.

**FIGURE 5** Changes in the position and extent of stands of *Sparganium erectum* and the edges of the inundated part of the channel in reach E, 2005–2020, interpreted from 2005, 2010, 2017 and 2020 Google Earth aerial images



Changes in retained fine sediment depth between March and August 2004 (Figure 4i–k) are similar under emergent (A, C, D means: 1.1, 1.1, 2.0) and submerged macrophytes (A, B, C, D means: 2.7, –0.6, 1.8, 1.4 cm), and are smaller across the bare bed (A, B, C, D means: –0.2, 0.6, 0.8, –0.7 cm).

The cover of bare bed (A, B, C, D means: 42%, 90%, 61%, 36%) and submerged macrophytes (A, B, C, D means: 49%, 7%, 33%, 55%) was quite high in the studied reaches, the cover of emergent macrophytes was relatively small in these near-straight reaches (A, B, C, D means: 9%, 4%, 6%, 9%). More extensive emergent cover was observed in nearby sinuous sections of the river, so an additional analysis was conducted on aerial imagery for a sinuous reach (E) that overlapped the downstream part of D. Here, stands of *S. erectum* were observed on the inner banks of the bends. Overlays of the inundated area from images captured in 2005, 2010, 2017 and 2020 illustrate how these stands formed the leading edge of vegetated point bars as they advanced into the channel (Figure 5). Between 2005 and 2020, the inundated area narrowed, moved laterally and became more sinuous. The water area shrank by 15%, the left bank showed a net advance of 2.4 m and the right bank showing a net retreat of 0.66 m.

### 3.3 | Isère

Between 1989 and 2015, four transects (Figure 6a–d) showed substantial aggradation of bar surfaces. Only locations covered by riparian vegetation (green lines, Figure 6) showed aggradation, with unvegetated parts of the transects showing relatively small changes in bed elevation. Considering only the vegetated area, vertical aggradation ranged from 0.96 to 1.61 m between 1989 to 1999 and 0.6 to 1.04 m between 1999 and 2015. The aggrading vegetated parts of the transects equate to the areas of fine sediment deposition observed by Serlet et al. (2018). When these fine sediment deposits are distributed

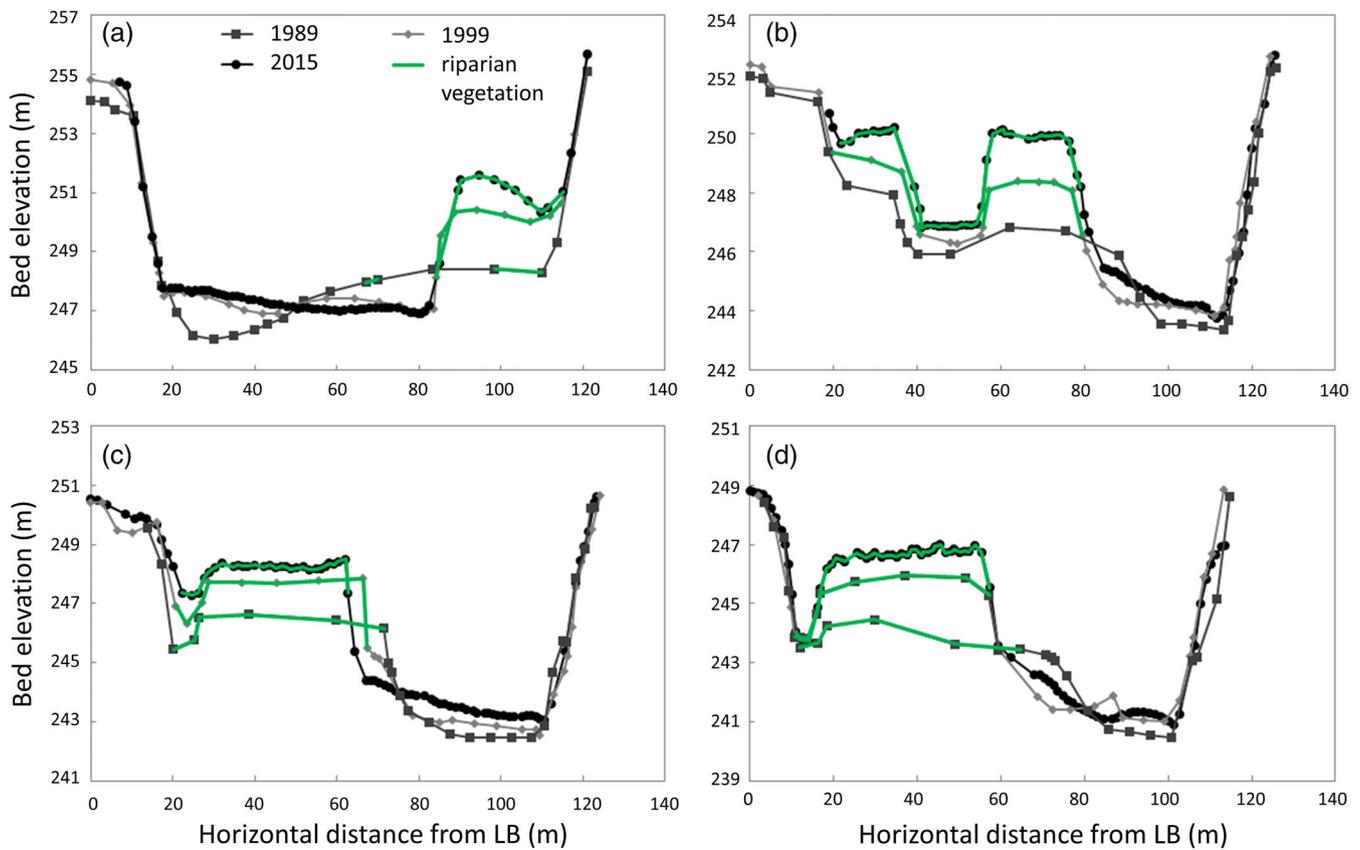
across the entire width of the active channel, they represent 0.41–0.71 m depth between 1989 to 1999 and 0.19–0.61 m depth between 1999 and 2015.

Vegetation covered 29.9% of the total reach area in 2015. Assuming all vegetated bars have fine sediment deposited to the average depth observed on the four transects, 180 000 m<sup>3</sup> of fine sediment was retained in vegetated bars between 1989 and 1990, equivalent to 0.39 m depth across the entire active channel. Between 1999 and 2015 a further ca. 111 000 m<sup>3</sup>, was retained in the vegetated landforms, equivalent to 0.23 m across the active channel area. Estimated annual deposition rates on the vegetated landforms are 3.9 (13) cm year<sup>–1</sup> between 1989 and 1999 and 1.4 (4.8) cm year<sup>–1</sup> between 1999 and 2015 considering the total active channel area (vegetated area).

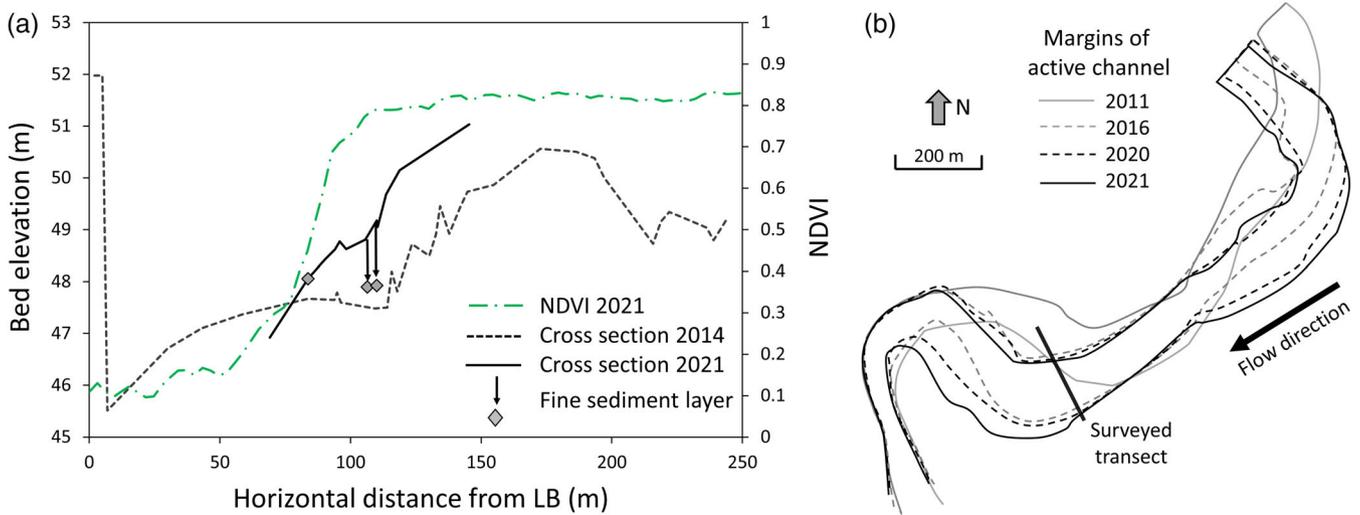
### 3.4 | Lower Tagliamento

The dynamic meandering reach on the lower Tagliamento shows significant erosion on the outer bank of the study meander bend and significant aggradation and bank building on the inner bank (Figure 7). The transect surveyed in 2021 was restricted by dense vegetation to an area covered by younger woody vegetation that has encroached and grown over the last 7 years. Comparison of the 2021 with 2014 transects shows an average surface aggradation of 1.35 m over 7 years, associated with lateral migration of the inner bank by approximately 25 m towards the outer bank (Figure 7a). Analysis of planform changes over 10 years (Figure 7b) shows a lateral shift of the order of the active channel width. The vegetated area surveyed in 2021 is located within what was the low flow channel in 2011.

The depth of the fine sediment layer was only determined in the lowest part of the transect. However, it is reasonable to consider that everything above an elevation of 48 m is fine sediment, leading to an



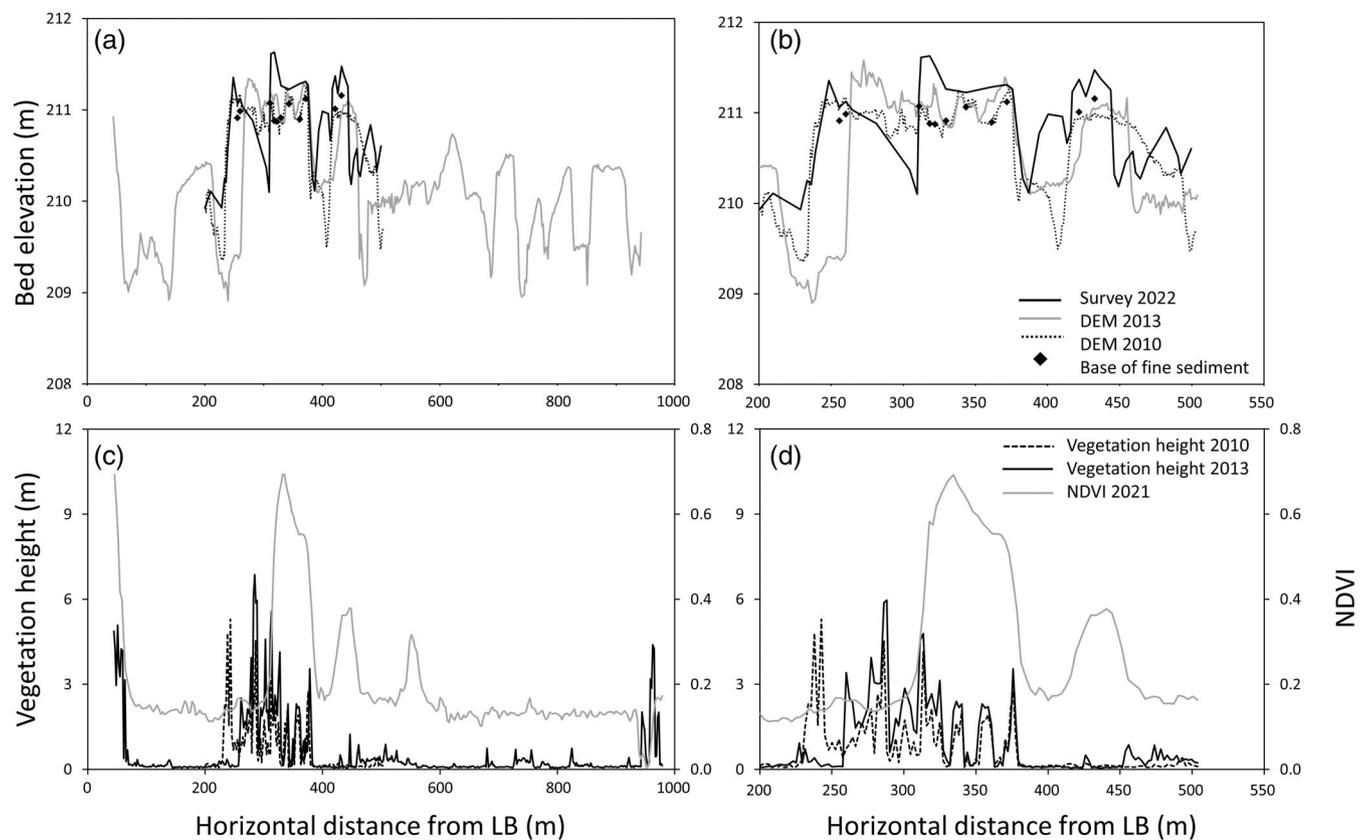
**FIGURE 6** Topographic change surveyed on four cross sections of the Isère. Green lines indicate the sections under riparian vegetation



**FIGURE 7** Reach A, Lower Tagliamento. (a) Topographic change surveyed on one transect in relation to the depth of fine sediment measured at the time of the 2021 survey. The NDVI index highlights the occurrence of vegetation across the transect in 2021. (b) Active channel edges from 2011 to 2021 highlighting planform changes and meander migration

estimate of up to 3 m depth of fine sediment and an average annual deposition rate of up to 30 cm year<sup>-1</sup>. Considering only the area under pioneer vegetation, an average depth of fine sediment of 1.35 m has accumulated between 2014 and 2021, equivalent to an

average deposition of 0.35 m across the area of the active channel. Of course, this is balanced to some degree by outer bank retreat, which we cannot estimate because the 2021 transect was limited to the point bar area.



**FIGURE 8** Reach A, Middle Tagliamento. (a) and (b) illustrate topographic change on one of three studied transects showing the complete cross-profile of the river extracted from 2010 to 2013 lidar data in relation to the local 2022 surveyed transect of the vegetated area with accompanying measurements of the base of the fine sediment layer. (b) presents an enlargement of (a) highlighting the length of the transect surveyed in 2022. (c) and (d) present information on the vegetation cover in 2021 represented by the NDVI index and the height of the vegetation extracted from lidar data for 2010 and 2013. (d) presents an enlargement of (c) highlighting the length of the transect surveyed in 2022

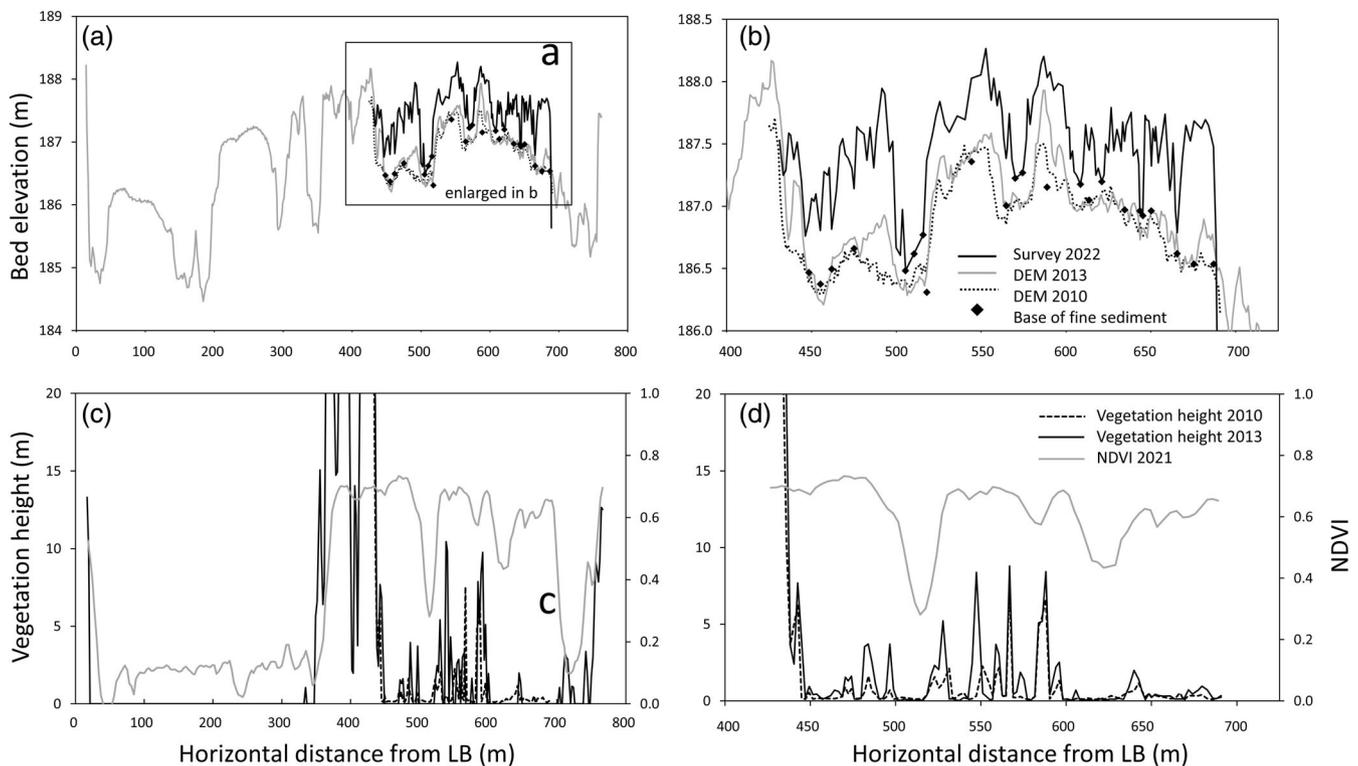
### 3.5 | Middle Tagliamento

In both reaches A and B, large areas have been colonized by riparian vegetation within the last 20 years. The 2021 (reach B) and 2022 (reach A) surveys were confined to these recently vegetated areas within the active channel as these are the only areas of significant fine sediment retention within the river channel apart from the established island in reach B, which is no longer aggrading and is at floodplain level, so is no longer a part of the active channel.

Reach A has a bar braided morphology with a small area of the central braid plain that has become colonized by vegetation over the last ca. 20 years. Vegetation patches appeared between 2003 and 2005 (Bertoldi & Gurnell, 2020) and vegetation currently covers about 8% of the active channel area. Figure 8(a) shows a transect across the entire braid plain estimated from a 2013 airborne lidar survey, with the shorter 2021 surveyed transect topography, a short transect estimated from 2010 lidar data, and 2021 measurements of the base of the fine sediment layer superimposed. These data are enlarged to show only the length of the 2021 transect in Figure 8(b). Vegetation height in 2010 and 2013 estimated from lidar data, and the extent of the vegetated area in 2021 estimated using the NDVI index, are

shown for the entire braid plain in Figure 8(c) and for the 2021 survey area in 2021 in Figure 8(d). Vegetation height, estimated from lidar data, was typically <5 m in 2010. During the last decade the vegetation has continued to grow in the central part of the active channel, with some erosion towards the left bank (compare 2010 and 2013 lidar estimates, Figure 8d) and some more recent vegetation encroachment towards the right bank (note the secondary peak in NDVI, Figure 8d). The measured depths of fine sediment (black diamonds, Figure 8b) are confined to the elevated parts of the 2021 transect, corresponding with the peaks in NDVI in 2021 (Figure 8d), and largely correspond to the 2010 topographic surface. A similar pattern was revealed in the other two surveyed transects.

There were few floods between 2004 and 2012, so the sparse shrubs present in 2010 retained minimal fine sediment. The 2013 bed surface shows a few areas of aggradation compared with the 2010 surface (e.g. between ca. 250 and 325 m and between 350 and 370 m across the transect, where significant vegetation cover was present in 2010). In the vegetated area, an average 0.36 m depth of fine sediment accumulated between 2010 and 2021, corresponding to an average depth of 0.03 m when distributed across the entire active channel.



**FIGURE 9** Reach B, Middle Tagliamento. (a) and (b) illustrate topographic change on one of three studied transects showing the complete cross-profile of the river extracted from 2010 to 2013 lidar data in relation to the local 2021 surveyed transect of the vegetated area (excludes the established island at the LB end of the transect, which has remained at the same elevation [floodplain level] for ca. 20 years and so is not part of the active channel) with accompanying measurements of the base of the fine sediment layer. (b) presents an enlargement of (a) highlighting the length of the transect surveyed in 2022. (c) and (d) present information on the vegetation cover in 2021 represented by the NDVI index and the height of the vegetation extracted from lidar data for 2010 and 2013. (d) presents an enlargement of (c) highlighting the length of the transect surveyed in 2021

At present, about 28% of the active channel in reach B is vegetated (excluding the large central island). This vegetation has established since 2003/4 across a previously open gravel surface between the established island and the right bank of the braid plain. Three transects were surveyed across this area and Figure 9 presents observations from one transect. Figure 9(a) shows a transect across the entire active channel extracted from 2013 lidar data, with the shorter 2022 transect, a transect derived from 2010 lidar, and the base of the fine sediment layer measured in 2022 superimposed. Figure 9(b) shows the same data for the length of the 2022 transect. This topographic and sediment retention data can be compared with vegetation data for the same transect lengths (Figure 9c, d), including vegetation height extracted from 2010 and 2013 lidar data and the extent of vegetation in 2021 represented by the NDVI index. The tall vegetation on the established island is clearly visible in Figure 9(c). In the more recently vegetated area (Figure 9d), vegetation was typically <2 m tall in 2010, but was approaching 10 m by 2013, and the vegetation cover is now continuous, as indicated by the 2021 NDVI data.

Comparison of the bed surface in 2010, 2013 and 2022 shows significant, widespread aggradation across the vegetated area (Figure 9b). The most densely vegetated areas show a surface

elevation in 2022 that is similar to the established island. Using the measurements of the depth of fine sediment as a guide, the vegetated area aggraded by approximately 0.14 m between 2010 and 2013 and 0.49 m between 2013 and 2022. The measured depths of the fine sediment layer largely correspond to the 2010 gravel surface, illustrating the relationship between vegetation colonization-growth and fine sediment retention. When averaged across the entire active channel (i.e. excluding the area of the established island), fine sediment retained by vegetation accounted for an average aggradation of 0.15 m between 2010 and 2022.

### 3.6 | Comparison of results from the studied river reaches

Fine sediment retention in the studied reaches is summarized in Table 3. These results illustrate sizeable and highly variable quantities of fine sediment retained, and the overriding importance of vegetated areas of the active channel bed for fine sediment retention in all of the studied reaches. Comparisons among the studied reaches according to their unit stream power are displayed in Figure 10, by presenting the observed fine sediment depths normalized for the average

TABLE 3 Fine sediment retention and dominant engineer plants in the study river reaches

River	Reach	Average <sup>b</sup> sediment retained across active channel area by vegetation (kg m <sup>-2</sup> )		Bare river bed: Average sediment retained <sup>c</sup> (kg m <sup>-2</sup> )	Submerged plants: Average sediment retained <sup>c</sup> (kg m <sup>-2</sup> )	Emergent plants: Average sediment retained <sup>c</sup> (kg m <sup>-2</sup> )	Emergent vegetated landforms: Average sediment retained <sup>c</sup> (kg m <sup>-2</sup> )	Main engineer plant species		
		Average <sup>b</sup> sediment retained across active channel area (kg m <sup>-2</sup> )	Average <sup>b</sup> sediment retained across active channel area by vegetation (kg m <sup>-2</sup> )					Submerged macrophytes	Emergent macrophytes	Riparian-marginal plants
Blackwater (Spring 2009)	A	513	454	201	71	598	942	<i>S. emersum</i>	<i>S. erectum</i>	<i>Phalaris arundinacea</i>
	B	346	303	135	-	413	850		<i>S. erectum</i>	<i>Phalaris arundinacea</i>
	C	466	412	73	38	398	827	<i>S. emersum</i>	<i>S. erectum</i>	<i>Typha latifolia</i>
Frome <sup>d</sup> (March 2004)	A	34	30	13	24	181	-	<i>Ranunculus</i> spp.	<i>S. erectum</i>	<i>Phalaris arundinacea</i> <i>Salix viminalis</i>
	B	23	18	6	42	0 <sup>a</sup>	480	<i>Ranunculus</i> spp.	<i>S. erectum</i>	<i>Phalaris arundinacea</i>
	C	23	23	0	34	235	-	<i>Ranunculus</i> spp.	<i>S. erectum</i>	<i>Phalaris arundinacea</i>
	D	113	111	11	33	94	979	<i>Ranunculus</i> spp.	<i>S. erectum</i>	<i>Phalaris arundinacea</i>
Isère (2015)	A	992	992	-	-	-	3310	-	-	<i>Salix alba</i> <i>Phalaris arundinacea</i>
Lower Tagliamento (2021)	A	560	560	-	-	-	2160	-	-	<i>Populus nigra</i>
Middle Tagliamento (A-2022, B-2021)	A	46	46	-	-	-	576	-	-	<i>Populus nigra</i> <i>Alnus incana</i>
	B	294	294	-	-	-	1024	-	-	<i>Populus nigra</i> <i>Alnus incana</i>

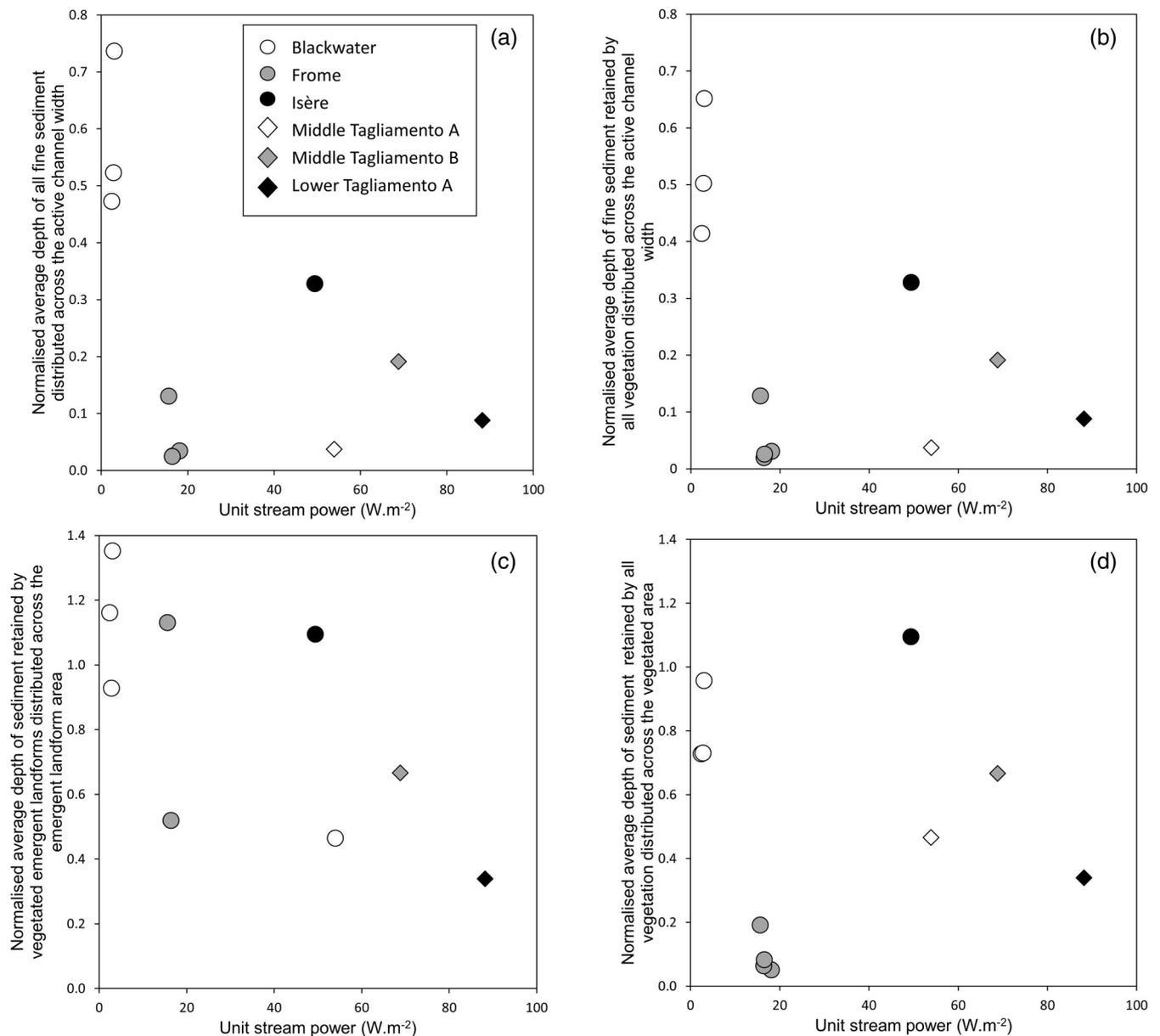
Note: -, cover type not present in this reach.

<sup>a</sup>Very low areal cover of this type.

<sup>b</sup>Estimated by distributing sediment retained across entire active channel width.

<sup>c</sup>Estimated by distributing sediment retained across the area occupied by the cover type.

<sup>d</sup>Reach E excluded because no sediment depth measurements.



**FIGURE 10** Normalized depths of fine sediment retained within the studied river reaches in relation to the unit stream power of the 2 year return period daily average discharge. (a) Average total fine sediment depth distributed across the active channel width; (b) average fine sediment depth retained by all vegetation distributed across the active channel width; (c) average fine sediment depth retained within emergent vegetated landforms distributed across the area occupied by emergent landforms; (d) average depth of all fine sediment retained by vegetation distributed across the vegetated area

flow depth for  $Q_2$  in a channel of the given active width and gradient with standardized flow resistance.

Figures 10(a,b), respectively, plot the total fine sediment and that retained by vegetation distributed as an average normalized depth across the active channel width. Both graphs show the elevated sediment retention in the channelized Blackwater and Isère reaches in comparison with the more naturally formed channels of other reaches with similar unit stream power. Figures 10(c,d) show fine sediment retained within emergent vegetated landforms and retained by all vegetation with the normalized depths computed across the area of the bed occupied by the landforms or all vegetation, respectively. In

particular, values around 1 in Figure 10(c), indicate that the emergent landforms on the channelized Blackwater and Isère, and reach D of the Frome are probably approaching a maximum in relation to current flows.

## 4 | DISCUSSION

In our discussion we first consider some detailed aspects of the studied sites to give some perspective on the transferability of our observations (section 4.1). We then revisit our research questions and

other generalizations indicated by our results (section 4.2). Finally (section 4.3), we place our results into a broader context by comparing them with published estimates of fine sediment quantities retained as surface drapes or within the coarser bed matrix of gravel bed rivers.

#### 4.1 | Interpretation of observations at individual studied sites

Our preliminary analysis suggests that large quantities of fine sediment are retained within the active channel of rivers ranging in width from 6 to 800 m, gradient from 0.0008 to 0.0040 m m<sup>-1</sup>, and unit stream power from 2.4 to 88.2 W m<sup>-2</sup> (Table 2). Normalized sediment depths (Figure 10a–d) suggest both a declining upper limit to fine sediment retention by vegetation as unit stream power increases and also greater normalized sediment depths in channelized rivers following a period of adjustment than in more natural rivers of similar stream power. These generalizations are tenuous when based on such a small number of case studies, so we raise some specific points in relation to the studied sites that may help in subsequent interpretations based on a larger sample of cases.

The Blackwater and the Isère are both channelized rivers and this has undoubtedly affected their fine sediment retention. At least two (A, C) of the Blackwater reaches have been modified in the recent past by deepening and widening, with one reach (C) occupying a straight channel created in the 1980s to make space for road construction. Major vegetated side bars and benches retain sediment in all three reaches and, based on Figure 10(c), probably indicate a new floodplain being constructed within the previously enlarged channel. Unlike the Blackwater, the Isère is confined between embankments which are elevated well above the surfaces of the vegetated bars that retain large quantities of fine sediment. The bars seem to be approaching an upper limit for their surface elevation (Figure 10c) since the rate of surface aggradation of the bars was notably lower between 1999 and 2015 than between 1989 and 1999. This suggests that the vegetated surfaces are approaching a 'bankfull' level and that the active channel width is approaching a value that is less than the between-embankment width.

The remaining study reaches are largely unaffected by human modification, although reaches C and D on the Frome were straightened in the past and the Lower Tagliamento reach has some bank erosion control structures in the downstream part.

One important characteristic of the Frome is that the channel appears to be narrowing and increasing in sinuosity within an historically wider channel planform as a result of inputs of fine sediment from agricultural land since at least the late 19th century (Grabowski & Gurnell, 2016; Gurnell & Grabowski, 2016). Our observations in reach E (Figure 5) support the contention that this processes of narrowing and sinuosity change is being led by trapping and stabilization of the fine sediment by *S. erectum* growing along the inner submerged edges of river bends.

The three reaches of the Tagliamento have different planforms. The Lower Tagliamento is actively meandering. Inner bank

aggradation and advance is driven mainly by the deposition of uprooted *P. nigra*, which trap sediment and sprout to produce tree-cored, vegetated scroll bars that further aggrade to floodplain level (Zen et al., 2017). The two reaches of the Middle Tagliamento support multi-thread planforms with reach A being predominantly bar braided and B island braided. These reaches have similar width, gradient and stream power, but a crucial difference is that reach A is drier than B (Gurnell & Bertoldi, 2020; Gurnell & Petts, 2006). Lower groundwater levels within the alluvial aquifer are associated with slower growth rates of the engineer tree species *P. nigra* and *Alnus incana* in reach A. Indeed, Gurnell and Petts (2006) highlighted water availability and tree growth performance as key factors contributing to differences among all of the three Lower-Middle Tagliamento reaches, because faster growing trees are more likely to survive flood disturbance events of any given magnitude-frequency.

#### 4.2 | Revisiting the research questions

##### 4.2.1 | Question 1: Are there differences in the proportions of fine sediment retained by vegetation on the beds of active river channels of different size, gradient and planform?

All studied river reaches reveal that vegetation retains virtually all fine sediment stored on the river bed surface. Rivers with higher total and unit stream power (functions of river gradient and width) retain negligible fine sediment beyond vegetated areas. Indeed, there is a clear contrast between the Blackwater and Frome reaches, where 88%–96% and 78%–100%, respectively, of the fine sediment is retained by vegetation and the other studied reaches, where all fine sediment is retained in and around vegetation. Thus, the proportions of fine sediment retained by vegetation appear to vary with river size and gradient. It is difficult to disentangle the influence of planform from river size because planform changes progressively across the studied rivers as their width and stream power increases.

##### 4.2.2 | Question 2: Are there differences in the locations of fine sediment retained by vegetation within active river channels of different size, gradient and planform?

There are major differences in the locations of fine sediment retained as the studied reaches increase in size-width and total or unit stream power, which incorporate gradient. Perhaps the most important contrast among the studied reaches involves submerged and emergent aquatic plants, which can only survive and then trap fine sediment on the beds of low energy, rivers, whereas higher energy rivers depend upon riparian vegetation to retain fine sediments. In the studied rivers, the Blackwater has the lowest unit stream power, and the emergent macrophyte, *S. erectum*, grows widely across the submerged channel bed, retaining significant

quantities of fine sediment. The Frome has a higher unit stream power than the Blackwater and *S. erectum* is only observed along the margins of the submerged river bed, where it retains significant quantities of fine sediment, especially along the water edge of the inner bank of bends. Submerged macrophytes on the Blackwater do not retain significant fine sediment, whereas those on the Frome do retain fine sediment. This likely reflects the different morphology of the dominant submerged species on the Blackwater and Frome (respectively, *S. emersum* and *Ranunculus* spp.). Additionally, in these low energy rivers, marginal herbaceous plants such as *Phalaris arundinacea* retain and reinforce sediment further building the submerged landforms as they emerge above low flow water level, whereas in larger, higher-energy rivers, large woody plants are the main emergent landform engineers (Gurnell & Bertoldi, 2020).

In larger rivers, the growth performance and elevation of the woody species within the active channel are as important as the flow disturbance regime in driving fine sediment retention (Francis, 2006, 2007; Corenblit et al., 2007, 2009). Since most riparian tree species show greatest growth performance when their roots can access groundwater, elevation within the active channel has opposing effects on the disturbance and the growth performance of riparian trees. These opposing factors lead to sediment retention at different elevations in the active channel and thus the potential inundation frequency and aggradation rates that are observed on vegetated patches. In addition, the spatial distribution of vegetated fine sediment features varies between single thread (lateral bars, often involving scroll bar development) and multi-thread (mid-channel bars and islands) with some streamlining of island edges by tree-cored scroll development on transitional reaches (Gurnell & Petts, 2006).

The differences in the locations of retained fine sediment and emergent landforms among the studied river reaches is also relevant to fine sediment residence time. In the two braided study reaches (Middle Tagliamento reaches A and B), fine sediment retention by woody vegetation is associated with the development of islands. Some islands may become attached to the floodplain and persist as part of the floodplain for many decades and even centuries. However, most islands remain within the active channel and follow cycles of aggradation and erosion. An historical analysis of island turnover within the middle Tagliamento (including reaches A and B) has revealed highly variable rates of island turnover through time but has estimated that islands persist on average for less than 25 years with many turning over in less than 12 years (Zanoni et al., 2008), delaying the downstream transfer of the retained fine sediment by one or more decades. In the more naturally functioning single thread rivers studied, fine sediment that is not absorbed into emergent landforms may be subject to annual cycles of retention governed by aquatic vegetation growth in lower energy systems (e.g. Frome). Incorporation into mid-channel bars may also retain fine sediment for several years or more (e.g. Frome). However, if the fine sediment is incorporated into side bars and benches, it may be retained for decades or centuries in the floodplain at locations where this process is part of channel migration (e.g. Frome Reach E, Lower Tagliamento). Finally, we have provided fine sediment retention estimates for two channelized rivers, the

Blackwater and Isère. Fine sediment retention in benches along the Blackwater represents channel adjustment and recovery from past management and so the retained fine sediment is likely to remain in storage over decades until natural processes of channel migration are re-established. On the Isère, reinstatement of lateral channel movement is prevented by embankments and so the dynamics of stores of fine sediment within vegetated alternate bars, now that the bars appear to have aggraded to 'bankfull' level, is uncertain. The bars may simply stabilize to create a narrowed channel that retains minimal fine sediment or the bars may gradually migrate within the embanked corridor forming dynamic stores of fine sediment particles with erosion and deposition in approximate balance. However, the final fate of the bars is likely to remain unknown because the vegetation and sediment are currently being managed to maintain flow conveyance within the embanked channel.

#### 4.2.3 | Other generalizations

Our six case studies illustrate a gradient in total and unit stream power through which submerged, emergent, riparian herbaceous, and riparian woody vegetation in turn take on the role of river engineers. Each vegetation type can retain notable quantities of fine sediment within active channels in an appropriate river energy setting and give rise to distinct landforms that reflect the engineer species, broad environmental setting (e.g. moisture availability), and river flow and sediment transport regimes. The quantities of retained sediment are also temporally variable, as illustrated by changes in sediment retention by aquatic macrophytes over seasonal (Frome) and annual (Blackwater) timescales, and as channels recover from channelization (Blackwater), and by riparian trees over years to decades following large floods (Tagliamento) and major human interventions (Isère).

Our observations concerning sediment retention by aquatic macrophytes are similar to flume experiments that highlight differences in retention between emergent and submerged vegetation, among plants of differing flexibility, and under differences in the bed area affected by vegetation (Hu et al., 2018; Ortiz et al., 2013). The potential of emergent macrophytes to retain fine sediment is emphasized by Zierholz et al. (2001) who observed the equivalent of 4.7 years of annual sediment production from a 2175 km<sup>2</sup> catchment retained by a 25% emergent macrophyte cover developed across an incised channel bed. Zierholz et al. suggest that cycles of channel cut and fill are characteristic of their Australian catchment with emergent aquatic plants driving the fill phases. Observations of sediment retention and transfer through drainage ditches by Lecce et al. (2006) indicate the importance of seasonal vegetation growth within the ditches for sediment retention. The complexity of vegetation-related landform-building processes has been monitored in the field by O'Briain et al. (2022), who document aquatic plant colonization, sediment retention and landform-building in an overdeep river in Ireland to produce a diverse mosaic of submerged and emergent landforms. Lastly, a broad-scale landform assessment of much lower gradient river

landscapes (<0.0005) than our case studies (Larsen, 2019) stresses the crucial multi-scale effects of flow-vegetation-sediment feedbacks that completely dominate such river landscapes and lead to many different landform assemblages built on vegetation-retained sediments.

We have not been able to find any similar study quantifying fine sediment retention over rivers of widely varying energy where the plant engineers range from riparian trees to submerged aquatic plants. However, the above examples related to aquatic and marginal plants and other studies documenting total sediment retention by large (dead) wood pieces (Parker et al., 2017; Sutfin et al., 2021; Welling et al., 2021) all indicate that landform building by vegetation within river channels is an important process that demands more research attention.

### 4.3 | Sediment storage in and on river beds

In this Special Issue in honour of Professor Walling we compare our estimates with others made using Lambert and Walling's (1988) method of quantifying silt and finer sediment in mantles on river beds and stored within the gravel matrix. Lambert and Walling (1988) quantified fine sediment using water sampled from inside a ca. 1 m deep metal cylinder driven ca. 5 cm into the river bed following disturbance of the water column and bed sediments. Their approach has been widely applied because it consistently samples sizeable areas of river bed and quantifies the most biogeochemically important component of the fine sediments on and in the bed, but application of the method is limited to shallow (<1 m) rivers. Differences in measurement methods, scales, precision and accuracy make comparisons with our observations extremely tentative, not least because of our inclusion of the sand fraction.

Synthesizing observations of average bed sediment storage at sites on English rivers (Collins et al., 2005; Collins & Walling, 2007a, 2007b; Lambert & Walling, 1988; Walling et al., 1998; Walling et al., 2003; Wilson et al., 2004), groundwater-fed rivers draining agricultural catchments (Frome, Pang, Piddle, Lambourn, Tern, Wylye) show average bed sediment storage estimates in the range 840–2391 g m<sup>-2</sup>, rivers with a lower groundwater component in south-west England (Leadon, Tone, Torridge) have average values of 1480, 740, 870 g m<sup>-2</sup>, respectively, and in northern England (Aire, Calder and Swale) values of 304, 777 and 186 g m<sup>-2</sup>, respectively. Observations elsewhere in Europe include the low gradient Sanginjoki, Finland (Marttila & Kløve, 2014) and Isábena, Spain (Piqué et al., 2014) with averages of 1332 and 456 g m<sup>-2</sup>, respectively. By including sand, our estimates are a lot higher (Table 3) but clearly illustrate the potential importance of vegetation as an additional in-channel sediment store. Estimates for the bare river bed on the Blackwater and Frome are the most relevant comparisons. The Blackwater estimates are up to two orders of magnitude higher, reflecting the fact that even the bare bed in this small, low energy river is always close to emergent aquatic plants allowing deep accumulations of fine sediment to mask most areas of the bed apart from a narrow strip where gravel is exposed. The Frome observations, although considerably higher than those

reported above, are probably comparable given the inclusion of sand in our estimates, and a comparison of these 'bare bed' estimates with those under emergent plants shows the relative importance of vegetation for sediment retention within the wetted channel. The even higher quantities in emergent landforms reveal an additional important in-channel sediment store.

## 5 | CONCLUSIONS

Fine sediment retained within active river channels is challenging to estimate but is potentially an important component of catchment sediment budgets; has a variety of impacts on the hydrological, geomorphological and ecological functioning of river systems; and represents a potentially important store of pollutants. Major advances in field and laboratory techniques led by Professor Walling over the last four decades have allowed fine sediment forming surface drapes and infiltrating the coarse bed matrix of gravel rivers to be quantified and its biogeochemical properties to be revealed. Our preliminary assessment of sand and finer sediment retention within a small sample of river reaches of varying size, power and planform, suggests that vegetation can retain and stabilize sizeable quantities of sediment within active river channels. The degree to which our results are representative of the true importance of vegetation will only be assessed fully when further studies aimed specifically at this issue generate robust data across a larger number of rivers.

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### DATA AVAILABILITY STATEMENT

The data underpinning the analyses presented in this article are provided in a supplementary file.

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