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Controls on fluvial grain sizes in post-glacial landscapes

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Abstract. The grain sizes of sediments in channels have been linked to landscape characteristics, such as flow distance from headwaters, topographic relief, lithology and climate, in landscapes with little past or present glacial influence. Few studies have explored the controls on sediment characteristics in formerly glaciated landscapes. In this study, we document river surface grain sizes at 279 localities across Scotland. We collect photographs of gravel bars through a citizen science survey, Scotland's Big Sediment Survey. Grain sizes distributions are extracted from the photographs using both manual and automated techniques. We investigate whether grain sizes can be correlated and predicted from environmental variables (e.g., basin slope, flow distance from headwaters) through Spearman's correlation statistics and random forest regression modelling. In contrast to other studies that have primarily focused on non-glaciated landscapes, we find no apparent controls on surface grain sizes in channels across Scotland. Specifically, we find no significant Spearman's relationships between d84 and environmental variables; the strongest relationship was found between d84 and average basin aridity with a weak r^2 value of 0.29. We also find that the predictability of our random forest model is poor and only captures 22% of the variance of d84. We find no correlation between grain size and flow competence, which suggests that sediment is both transport-limited and supply-limited. We propose that Scotland's post-glacial legacy drives the lack of sedimentological trends documented in this study, and that changes in landscape morphology and sediment sources caused by glacial processes lead to a complete decoupling between fluvial sediment grain size and environmental variables. This interpretation aligns with other studies that have highlighted the ongoing role of the post-glacial legacy on landscape evolution in tectonically quiescent terrains, both in Scotland and globally. Our results suggest that fluvial sediment grain size cannot be predicted by a global model based on environmental variables in post-glacial landscapes.

1 Introduction

The delivery of sediments through river basins influences river morphology, hazards (e.g., flood risk), habitat value (e.g., spawning of salmonids) and landscape response to climatic and tectonic forcings. The characteristics of sediments delivered from hillslopes to fluvial systems influences the properties of sediments transported by rivers which are eventually exported to terminal sedimentary sinks (e.g., lacustrine and coastal environments, Attal and Lavé, 2006; Parker, 1991; Sklar et al., 2006; Whittaker et al., 2010).

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Bedload grain sizes, the focus of this study, are a key characteristic for understanding fluvial environments. For example, bedload grain sizes influence river transport conditions, provide information on sediment sources, control rates of bedrock incision (e.g., Sklar and Dietrich, 2004) and the width of channels (e.g. Baynes et al., 2020; Finnegan et al., 2005; Li et al., 2020a, b). Initial grain size distributions delivered to rivers are controlled by fragmentation, weathering and rock mass structure (e.g., Sklar, 2001; Sklar et al., 2017; Wells et al., 2008). Individual sediment particles then reduce in size, primarily by abrasion, during downstream fluvial transport (Sternberg, 1875). The distributions of fluvial grain sizes have therefore been correlated to the longitudinal flow distance along a channel (e.g., Gomez et al., 2001; Moussavi-Harami et al., 2004; Rice and Church, 1998; Sklar et al., 2006). Downstream fining trends can be offset by variations in the supply of sediment (e.g., sediment input from landslides) and the transport ability of a channel (e.g., Attal and Lavé, 2006; Attal et al., 2015; Sklar et al., 2006).

A handful of studies have further explored the effects of landscape characteristics, such as topography, lithology and climate, on the size distributions of channel sediments at the local scale. For example, hillslope gradient has been shown to be one of the most important topographic controls on grain sizes (Sklar et al., 2017), and several studies have shown fluvial grain sizes to increase with hillslope steepness (e.g., Attal et al., 2015; Purinton and Bookhagen, 2021; Whittaker et al., 2010). Attal et al. (2015) found hillslope grain sizes to increase with hillslope steepness and erosion rates in the Feather River basin, Northern California. They showed an increase in the channel sediment grain sizes to arise from an increase in the flow competence (i.e., ability of a river to transport sediment) and changes in hillslope sediment sources from soil-mantled to mass-wasting processes (e.g., landslides, debris flows). A similar trend was documented by Whittaker et al. (2010) in the Appenine Mountains of Italy, whereby coarser fluvial grain sizes were measured in landslide-dominated areas. Likewise, the importance of lithology in controlling bedload characteristics, including grain sizes, has been demonstrated by several studies (e.g., Mueller and Pitlick, 2013; Purinton and Bookhagen, 2021; Sklar et al., 2020). For example, Mueller and Pitlick (2013) showed that more erodible rock types, such as sedimentary rocks, were associated with higher sediment yields in comparison to more resistance rocks, such as granitic rocks, in the Rocky Mountains, USA.

Studies have tested the predictability and controls of fluvial grain sizes and sediment substrate cover at large spatial scales by documenting sediment characteristics across multiple basins with gradients in topography, lithology, climate and hydrology (Abeshu et al., 2021; Haddadchi et al., 2018; Mugodo et al., 2006; Snelder et al., 2011). Given the large spatial extent of these studies, they have focused on applying data-driven machine learning techniques, such as a random forest regressor. These empirical models have used readily available environmental variables that broadly reflect the upstream network structure and sediment source characteristics of each locality, such as flow distance, basin slope, lithology and precipitation indices. Snelder et al. (2011) found that surface grain sizes could be reasonably well predicted from a random forest model for rivers across France which, outside high mountain environments, has largely not been glaciated. Their study found an r^2 value of 0.52 between the observed and predicted values, and identified channel slope, basin averaged slope and rock hardness to be the most important variables controlling the modelled grain sizes.

Research into controls on bedload grain sizes has largely focused on landscapes with no past or present glacial influence. Formerly glaciated landscapes are typically more complex than landscapes with no glacial influence. Key challenges associated with understanding geomorphic processes in post-glacial landscapes originate from the glacial modification of hillslopes and channels, such as decoupling of hillslopes from channels due to the over-deepening and widening of valleys by glaciers, or extensive glacial sediment drapes (e.g., till, moraines, paraglacial terraces) which influence sediment supply and transport capacity (Attal and Lavé, 2006; Ballantyne, 2019; Mason and Polvi, 2023; Reid et al., 2022; Whitbread et al., 2015). Such areas represent a significant fraction of global land (e.g., most of the UK, Scandinavia, North America) and their extent will inevitably grow as a result of glacial retreat driven by climate change. A key research avenue therefore includes exploring the applicability of global predictive grain size models, such as that proposed by Snelder et al. (2011) which was tested in a largely non-glaciated landscape, to post-glacial landscapes.

In this study, we adopt a similar approach to Snelder et al. (2011) and test whether grain sizes can be predicted in Scottish river basins. Scotland was deglaciated around 12 kyr ago following the disappearance of the British-Irish Ice Sheet (Ballantyne, 2019; Clark et al., 2018; Firth and Stewart, 2000; Shennan et al., 2009). Scotland has subsequently been in a phase of glacial isostatic uplift, with average present-day rates varying between 0.5 and 1.2 m/kyr (Bradley et al., 2023). Many Scottish river basins exhibit typical features of post-glacial landscapes, such as U-shaped valleys and paraglacial sediment stores, many of which contribute large quantities of material to modern rivers (e.g., Ballantyne, 2008). We consider the hypothesis that grain sizes can be reasonably well predicted from environmental variables similar to those outlined by Snelder et al. (2011) in Scottish river basins. That is, we question if 12000 years is a sufficient period to allow a formerly glaciated landscape to adjust its sediment characteristics to reflect local fluvial conditions. The corresponding null hypothesis is that grain sizes cannot be predicted.

To test our hypotheses, we develop a photograph-based methodology for gathering a spatially extensive dataset of grain size distributions. After a description of our photograph-based methodology, we describe the predictive variables and the random forest regressor model. Subsequently, we present our model predictions and discuss the complexities associated with documenting large-scale trends and controls on fluvial grain sizes in post-glacial landscapes.

2 Methods

2.1 Grain size data collection

Sediment characteristics, including grain sizes, are poorly documented in Scotland. In light of the limited grain size data available and the time-consuming nature of traditional field sediment surveys (Bunte and Abt, 2001; Wolman, 1954), we gathered surface sediment size data through a citizen science project, Scotland's Big Sediment Survey (SBSS). SBSS was designed through ESRI's Survey123 platform (https://survey123.arcgis.com/). Users were asked for two types of photographs: a context photograph of the sediment deposit, and a surface photograph of the sediment bar (see Figure 1 for examples). Users were

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requested to include an object for scale in the surface photograph (e.g., penknife, plastic card) and to take the photograph parallel to the bar from a known height (e.g., person's height, chest-height). Both of these measurements were then recorded by the user on the Survey123 form. Users provided the location of the sediment bar through either dropping a pin on a map (which was provided on the survey platform), uploading a geographic position or enabling the camera's location feature. Prior to sediment grain size extraction, all photographs and corresponding survey information were pre-screened for quality assurance (e.g. photos were removed with spurious locations). A total of 275 locations were obtained across Scotland from SBSS (Figure 1).

In addition to the locations collected through SBSS, we used Wolman Point Counts (Wolman, 1954) to survey the intermediate axis of 100 clasts at four locations (see Figure 1 for locations). At these sites, a tape measure was positioned on the sediment bar parallel to the river's flow direction, and sediment grains were measured every 50 cm.

2.2 Grain size extraction methods: PebbleCounts and manual counting

We examine trends in sediment sizes through photo-based measurements of the intermediate axis (b-axis) which we extract through automated and manual techniques. Automated and semi-automated techniques have received significant attention in recent years because they are typically less time-consuming and can be used to obtain a larger sample size (Harvey et al., 2022; Purinton and Bookhagen, 2019). Automated algorithms include both image segmentation (e.g., Detert and Weitbrecht, 2013; Purinton and Bookhagen, 2019) and texture-based approaches (e.g., Brasington et al., 2012; Westoby et al., 2015).

In this study, we apply PebbleCountsAuto which is an automated grain segmentation algorithm (Purinton and Bookhagen, 2019). PebbleCountsAuto initiates the segmentation process from both the grain colour and interstices. The algorithm then fits an ellipse to the segmented area from which the pebbles axes values are extracted. Purinton and Bookhagen (2019) compared PebbleCountsAuto to a manually measured control dataset at 12 sites in North-West Argentina and reported an average mean error of 0.15 ψ across several percentiles, where ψ represents the negation of the ϕ unit typically used to describe grain size data ($\psi = -\phi = \log2(\mathrm{mm})$). In this study, we also compare PebbleCountsAuto results to a manually measured control dataset, the procedures of which are described below.

Images are scaled in PebbleCountsAuto from the camera resolution, *R*, which is calculated from the camera's sensor height or width, *S*, focal length, *f*, image height or width, *I*, and the camera height, *h*, the latter of which is recorded in the survey data. The camera resolution is given by:

$$R = \frac{Sh}{fI} \quad (1)$$

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In this study, the average and maximum resolution of images processed through PebbleCountsAuto were 0.54 mm/pixel and 1.05 mm/pixel respectively. The lower detection limit of a pebble's b-axis length in PebbleCountsAuto is 20 pixels which equates to a minimum b-axis length of 21 mm with our maximum camera resolution of 1.05 mm/pixel. We conservatively truncate the grain size distributions at 25 mm for all photographs.

A potential user-derived uncertainty associated with the camera resolution of the photographs and the final grain size measurements originates from the height at which the photographs were taken. We perform a sensitivity analysis to test the influence of camera height on camera resolution with a standard consumer-grade camera (e.g., sensor height = 4.55 mm, focal length = 4.3 mm, image height = 3024 pixels). For example, an increase in height of 15 cm increases the camera resolution by 0.05 mm/pixel. Thus, for our average camera resolution of 0.54 mm/pixel, an increase in camera height by 15 cm increases the final grain size measurements by ≈ 10 % (see Table S2 in the Supplementary Data for full sensitivity analysis). We further discuss the overall influence of camera height-derived uncertainties in the sample comparison (Section 2.2.1).

Photos that could not be processed through PebbleCountsAuto due to issues with calculating camera resolutions (e.g., missing metadata) or significant segmentation faults were manually processed by overlaying a regular square grid with 100 line intersections (Kellerhals and Bray, 1971). Clasts were scaled according to the object placed in the image and the object's corresponding dimensions which were recorded on the survey platform. Ideally, the size of the grid applied to the photographs should be chosen so that no more than one grid intersection falls on one pebble. However, such a requirement is nearly impossible to fulfil where large grains span multiple intersections. Clasts that cover grid intersections n times were therefore counted n times following the voidless cube model presented by Kellerhals and Bray (1971). Overall, 37 % of the images obtained through SBSS were processed through PebbleCountsAuto and 63 % were processed manually.

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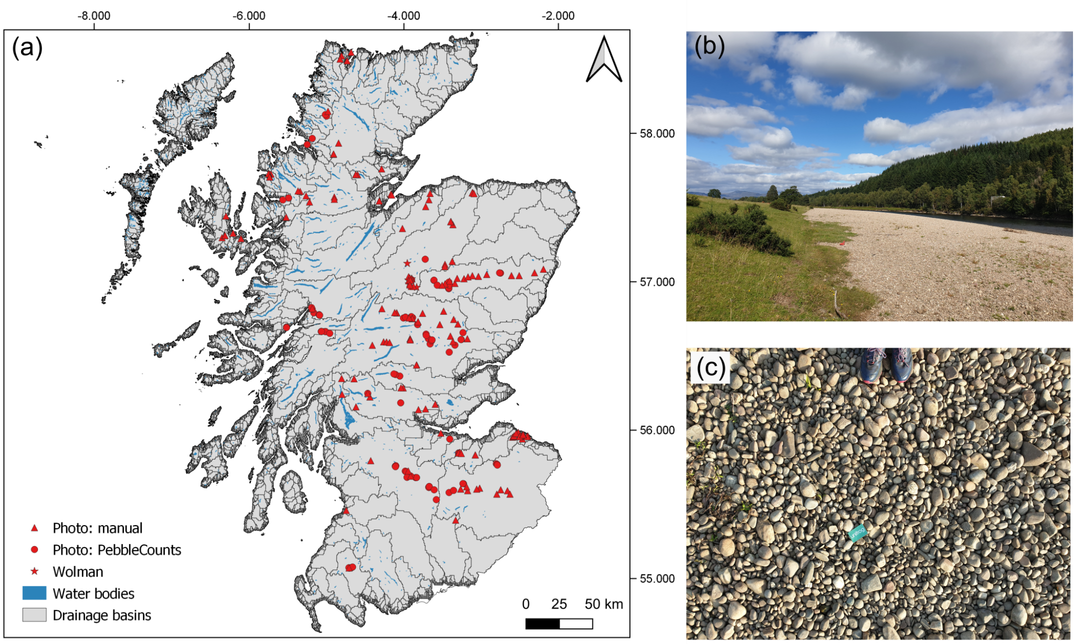

Figure 1. (a) Map of Scotland (focused on the mainland) showing 279 surveyed locations. Circles represent samples processed with PebbleCountsAuto, triangles show manually clicked sites, and stars represent samples measured using Wolman Point Counts. Water bodies are shown in dark blue and drainage basin outlines (15 arc-second resolution) in black (sourced from the HydroLAKES and HydroBASINS databases, (Lehner and Grill, 2013; Messager et al., 2016)). **(b)** Context photograph of gravel bar. **(c)** Top-down, surface photograph of sediment with a card that is 8.5 cm in length for scale.

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2.2.1 Comparison between grain sizing tools

To test the performance of PebbleCountsAuto, we compare the apparent 50th (d50) and 84th (d84) percentiles at 9 sites in the Tay basin to a manually measured control dataset. These sites represent a range of pebble sizes and lithologies, spanning from the Tay's source in the Highlands to upstream of its estuary (see Table S1 in the Supplementary Data for sample locations). All 9 sites have an image resolution of 0.47 mm/pixel. We exclude grains with a b-axis below 25 mm which is consistent with the minimum truncation value that we apply to our Scotland-wide dataset (see Section 2.2). We compare the 50th and 84th percentiles in mm by the mean error (*me*), normalised root mean squared error (*nrmse*) and r-squared linear regression coefficient (r^2). We also compare the 50th and 84th percentiles derived from PebbleCounts and the manually measured dataset using t-tests.

Error bars are plotted on both the manual and PebbleCounts measurements in Figure 2. With regards to our manually measured samples, we assess the impact of the largest clast covering multiple grid nodes using the method presented by Attal et al. (2015). Firstly, the largest clast was removed from the grain size distribution to estimate d50 and d84 percentiles; secondly, a large clast of the same size as our largest clast was added, covering the same number of grid nodes. Error bars on manually measured grain size figures represent the range of values between these scenarios. For PebbleCountsAuto measurements, we plot error values of +/- 10% to account for potential uncertainties associated with the height of the photograph. An uncertainty of ≈ 10% represents a change in camera height by 15 cm for a camera resolution of 0.47 mm/pixel (see Section 2.2).

We find that PebbleCountsAuto generally underestimates the grain sizes compared to manual measurements of photos, especially at the localities with larger grain sizes (sample sites 6-9, Figure 2). The PebbleCounts d84 measurements are statistically similar (p-value from t-test > 0.05, $r^2 = 0.94$) to the manual measurements whereas the d50 percentiles are different (p-value < 0.05, $r^2 = 0.73$). Likewise, the d84 comparison has a lower *nrmse* (0.28) than the d50 comparison (*nrmse* = 0.44, Figure 2).

Our PebbleCounts comparison aligns with results from other studies that have compared PebbleCounts to manually measured datasets (e.g., Chardon et al., 2022; Miazza et al., 2024). In line with our findings, these studies have shown that PebbleCounts generally underestimates grain sizes. These studies attributed these trends to over-segmentation issues which arise from inter-granular textures (e.g., veins, fractures), and irregular shadowing (Figure 2c). Visual observations of our PebbleCounts output images suggest that larger grains have more inter-granular textures (e.g., veins, fractures), which may explain the apparent over-segmentation at locations with larger grain size distributions (sample sites 6-9, Figure 2). Given the lower errors associated with the d84 percentile, we focus our analysis on this percentile.

2.3 Selection of environmental variables

We test the applicability of global empirical grain size models (e.g., Abeshu et al., 2021; Snelder et al., 2011) to Scottish river basins by using similar environmental variables and Machine Learning techniques. For each sample, we determine channel

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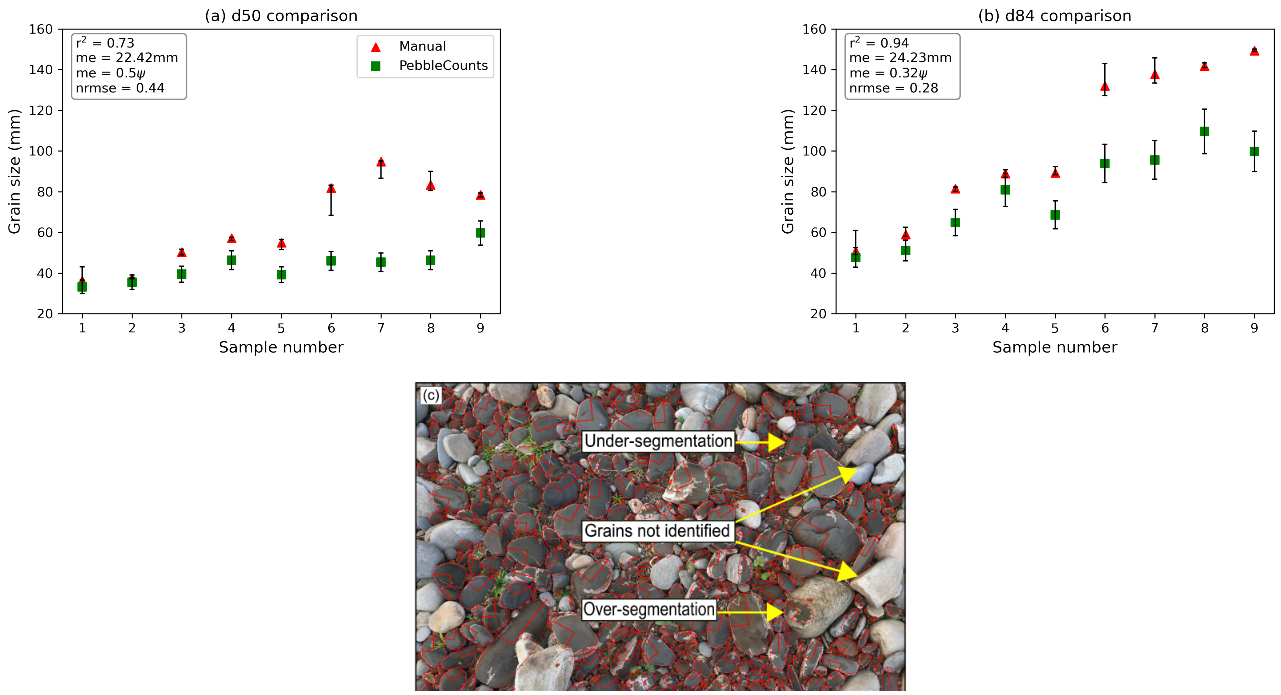

Figure 2. Figures **(a)** and **(b)** show comparisons between PebbleCounts and the manually measured control dataset at 9 sites in the Tay basin (see Table S1 in the Supplementary Data for sample locations). Error bars are plotted according to the procedure outlined in Section 2.2.1. The mean error (*me*), normalised root mean squared error (*nrmse*) and r-squared linear regression coefficient (r^2) are shown on figures **(a)** and **(b)**. Figure **(c)** shows an example of an output image from PebbleCounts. Common errors such as under-segmentation, over-segmentation and undetected grains are highlighted.

slope, elevation and flow distance in LSDTopoTools (Mudd et al., 2023) from a 5 m Digital Terrain Model (DTM) sourced from the Ordnance Survey (Ordnance Survey, 2021). Channel slope was averaged over 100 m. We delineate the upstream contributing basin area, and then calculate basin-averaged topographic metrics including basin area, slope and drainage density. We record basin-averaged aridity for each sample from a global aridity map by Zomer et al. (2022). For each of the sampled sites, we measure bankfull channel width from Bing Satellite Imagery. We define bankfull width as the distance orthogonal to the flow direction between either bedrock banks or the limit of vegetated bars on the edge of channels (e.g., Baynes et al., 2020).

Like other global empirical grain size studies, we calculate average bedrock erodibility of each sample's upstream basin. We attribute an erodibility value to every lithological unit present on a geological map of Scotland sourced from the British Geological Survey (BGS, 2021). We estimate each lithology's erodibility using an index developed by Campforts et al. (2020) and Clubb et al. (2023). The lithological erodibility index, L_E, incorporates approximations of rock strength, L_L, and the degree of metamorphism, L_M, on the assumption that stronger and highly metamorphosed rocks are less erodible (Clubb et al., 2023).

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L_E assumes that the erodibility of a unit is based on L_L and L_M for non-igneous rocks, and L_L alone for igneous rocks. L_L ranges from 2 (e.g., granite, gneiss) to 12 (e.g., unconsolidated deposits). Similarly, L_M varies from 2 (highly metamorphosed) to 12 (unmetamorphosed); sedimentary rocks are classified as unmetamorphosed. The lithological erodibility, L_E, is calculated as:

$$L_E = \frac{2}{7}L' \tag{2}$$

$$L' = \begin{cases} \frac{(L_M + L_L)}{3}, & \text{non-igneous rocks} \\ \frac{L_L}{2}, & \text{igneous rocks} \end{cases} \tag{3}$$

We refer the reader to Figure S2 in the Supplementary Data for the lithological erodibility map of Scotland.

Finally, we document the percentages of peat, alluvium, glacial till and glaciofluvial material in each sample's upstream basin (Haddadchi et al., 2018; Snelder et al., 2011). Superficial maps were downloaded from the British Geological Survey (BGS, 2021). A list of the environmental variables is provided in Table 1.

2.4 Random forest regressor model

To assess the relative importance of the environmental variables in controlling grain sizes, we apply the same methodology as Snelder et al. (2011) and use a random forest regression (RFR). RFR is a form of supervised Machine Learning which uses an ensemble of decision trees to predict a target variable (Breiman, 2001). Predictions are made by formulating unforeseen, multi-dimensional relationships between the input features. The model performance and apparent feature importance can then be evaluated by assessing the correlation between the observed and predicted grain sizes. In this study, we perform a leave-one-out-cross-validation (LOOCV) which trains the model on all but one sample and then evaluates the performance of the model on the excluded data point. This process is then repeated for each data point.

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Variable Name	Description	Data source
Aridity index	Mean basin ratio of annual mean potential evaporation to annual mean precipitation	Zomer et al. (2022)
Drainage density	Total stream length divided by drainage area	5 m DTM from Ordnance Survey (2021)
Drainage area	Upstream contributing basin area	
Basin slope	Mean basin slope	
Channel slope	Channel slope of sample averaged over 100 m upstream	
Channel elevation	Elevation of sample	
Flow distance	Longitudinal flow distance from a channel's most upstream source. A contributing area of 0.125 km^2 was used to define the beginning of a channel.	
Bankfull channel width	Distance orthogonal to the flow direction measured between banks	Bing Satellite imagery
Basin bedrock erodibility	Mean basin bedrock erodibility	BGS (2021), bedrock layer
Percentage of Till in catchment	Material deposited underneath a glacier without subsequent fluvial reworking	BGS (2021), superficial layer
Percentage of Alluvium in catchment	Material deposited by rivers	
Percentage of Glaciofluvial in catchment	Material deposited by glacial meltwater streams	
Percentage of Peat in catchment	Partially decomposed mass of vegetation	

Table 1. Description of environmental variables and their data sources.

2.5 Flow Competence and sediment entrainment

210 In a scenario where all grain sizes are available for transport, the grain size of the sediment mobilized by a river is expected to increase with flow competence (Bathurst, 2013; Whitaker and Potts, 2007). In this case, the grain size can be considered 'transport-limited', that is, limited by the ability of the river to transport a given grain size. In some situations, rivers are only provided with fine grained sediment; in such systems where there is a lack of coarse grains available for transport, the grain size mobilized by the river will be 'supply-limited' (Attal et al., 2015). Thus, the relationship between flow competence and grain size can provide information on sediment supply-limited and transport-limited conditions. Both scenarios may arise in

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our study area due to post-glacial processes affecting the distribution of sediment stores and the transport ability of channels. We therefore analyse this relationship to assess whether trends can be observed, that may reflect the dominance of one or the other of these conditions.

Flow competence is typically expressed as a function of shear stress (e.g., Buffington and Montgomery, 1997; Mueller and Pitlick, 2014), which is calculated from the hydraulic radius of a channel and other parameters (Shields, 1936). However, the hydraulic radius can be challenging to measure due to access to sampling locations, identification of reference conditions (e.g., reference discharge) for comparison across all sites, and unmanageable sample sizes. An alternative approach consists of using the relationship between unit discharge and grain size that has been explored by researchers based on experimental work and field data (Attal et al., 2015; Bathurst, 2013; Whitaker and Potts, 2007). In its simplest form, the equation is:

$$q_{ci} = aD_i^b \quad (4)$$

where q_{ci} is the critical unit discharge required for the entrainment of sediment of grain size D_i, a is a coefficient and b an exponent that should take the value of 1.5 for sediment of uniform grain size (Bathurst, 2013; Whitaker and Potts, 2007). The b exponent was found to vary between 0.15 and 1.3 based on a compilation of field data by Bathurst (2013) and Whitaker and Potts (2007), with the values being self-consistent within given datasets, and seemingly dependent on the flow regime (rainfall versus snowmelt-dominated; Bathurst (2013)), sampling method, and the definition of the grain size of interest D_i (taken as D_{max} in the study by (Whitaker and Potts, 2007)). Importantly, both studies showed a strong dependency of the relationship to the channel slope S. Considering that our dataset includes channel slopes spanning orders of magnitude, we believe that using a relationship that includes S as a controlling variable is essential.

Bathurst et al. (1987) proposed the following equation based on flume experiments using sediment of uniform grain size in the range 3-44 mm and slopes ranging between 0.0025 and 0.2 m/m:

$$q_c = 0.15g^{0.5}D^{1.5}S^{-M} \quad (5)$$

where q_c is the critical unit discharge required for the entrainment of sediment of grain size D, g is the acceleration due to gravity and M is an exponent found to vary in a narrow range: Bathurst et al. (1987) found a value of 1.12 in their experiments, while Bathurst (2013) found a value of 1.15 based on a compilation of flume data, close to the value of 1.17 ‘derived by Schoklitsch (1962) from the Shields equation and Manning-Strickler flow resistance equation’.

Equation 5 can be rearranged as:

$$D = [0.15g^{0.5}QS^M/W]^{2/3} \quad (6)$$

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where W is channel width and Q the discharge. If sediment grain size is transport-limited, i.e., controlled by flow competence, a power relationship can therefore be expected between the grain size D and the quantity ω_m (Attal et al., 2015), where

$$\omega_m = QS^M/W. \quad (7)$$

For the purpose of this Scotland-wide analysis, we assume that drainage area A can be used as a proxy for discharge and use the variable ω'_m that substitutes Q for A:

$$\omega'_m = AS^M/W \quad (8)$$

Attal et al. (2015) had found a significant power relationship between the grain size of surface sediment and ω'_m in tributaries of the Feather River, Sierra Nevada, California. The exponent derived from their dataset was 0.61, 0.53 and 0.4 for d50, d84 and d100, respectively, with an exponent closest to the expected 2/3 value for the median grain size d50.

Here, we use a value of 1.15 for the exponent M (Attal et al., 2015). We use the measured bankfull width (described in Section 2.3) to calculate ω'_m and make the assumption that the modelled percentiles (d50 and d84) are transported during the bankfull width's corresponding flow conditions, which is, by definition, the bankfull flow.

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3 Results

In this section, we present the following results: (1) national-scale map of grain sizes, (2) correlations between grain sizes and environmental variables outlined in Table 1, (3) RFR predictions and associated variable importances, and (4) flow competence analysis. We convert our grain size percentiles to the typical ψ scale for correlation statistics and RFR analysis. This allows direct comparison of statistical results with Snelder et al. (2011).

The d84 percentiles documented in this study range from 4.91 ψ to 8.64 ψ and follow a positively skewed distribution where the majority of the values fall between 5.7 ψ and 7 ψ (Figure 3). A map of the d50 percentiles is shown in the Supplementary Data (Figure S1). There is generally no discernible spatial patterns of grain size. Rivers along which multiple samples were taken show no obvious fining trends. The coarsest sediment (d84 in excess of 175 mm) is found both in the headwaters (e.g., Spey), in the middle reaches (e.g., Dee) or near outlets (e.g., Findhorn) of river catchments. Likewise, the finest sediment is found in diverse regions of the various river systems.

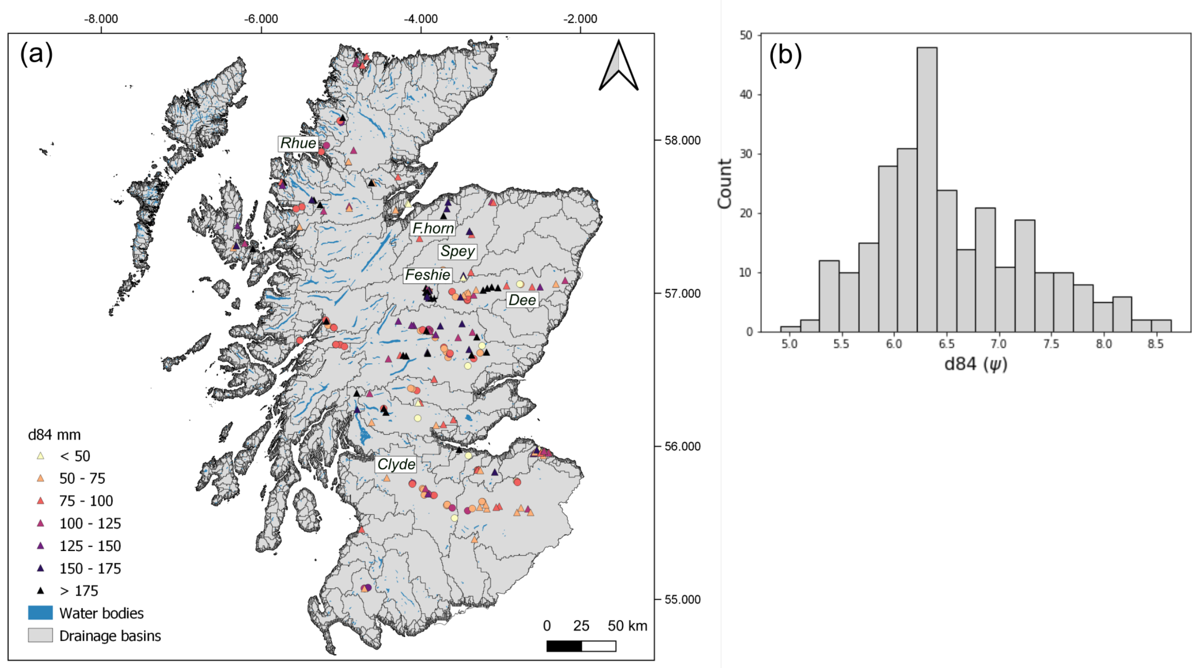

Figure 3. (a) Map of Scotland (focused on the mainland) showing 279 surveyed locations coloured according to d84 (mm). Circles represent samples processed with PebbleCountsAuto, triangles show manually clicked sites, and stars represent samples measured using Wolman Point Counts. Water bodies (<10 hectares) are shown in dark blue and drainage basin outlines (15 arc-second resolution) in black (sourced from the HydroLAKES and HydroBASINS databases, (Lehner and Grill, 2013; Messager et al., 2016)). Drainage basins that are referred to in the main text are labelled. **(b)** Histogram of d84 grain sizes converted to the ψ scale.

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Overall, grain size does not show any significant Spearman's correlations with the independent variables (Figure 4). The strongest correlations observed for the d84 are with the average basin aridity (0.29) and average basin bedrock erodibility (-0.26). The percentages of alluvium, peat and glaciofluvial material also display similar correlation values of ≈ 0.2.

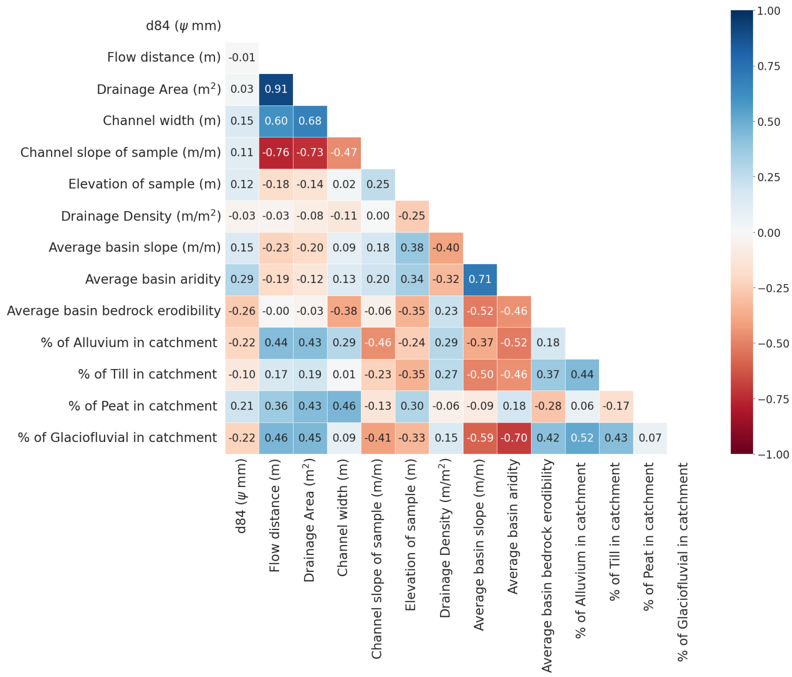

Figure 4. Spearman's correlations between measured grain size (d84) and various hydrological, climatic and topographic variables.

Results from the Random Forest Regressor model show the normalised importance of each environmental variable using the impurity reduction method, and the model's predictive ability (Figure 5). The most important variables modelled for the d84 are the average basin bedrock erodibility and channel slope of the sample, which have normalised importance values of 0.16 and 0.12, respectively. These variables presents some of the strongest Pearsons correlations with grain size (Figure 4). However, the predictive ability of the RFR model is poor, which raises caution to the interpretation of variable importance. When validated against the unseen testing data through the LOOCV method with all features included, the RFR presents a $nrmse$ of 0.10 ψ and r^2 of 0.22. Similar results are also observed for the d50 (see Figure S3 in the Supplementary Data).

As discussed in Section 2.5, the relationship between ω'_m, which we use a proxy for flow competence, and grain size can provide information on supply-limited and transport-limited grain size conditions. In supply-limited systems, there would be an apparent grain size threshold that would not be exceeded, even at high flow competence. A power relationship between grain size and ω'_m would be expected to reflect transport-limited grain size conditions. Neither of these is obvious in our Scotland-wide d84 dataset (Figure 6a): a wide range of grain sizes is observed across a wide range of flow competences. Similar results

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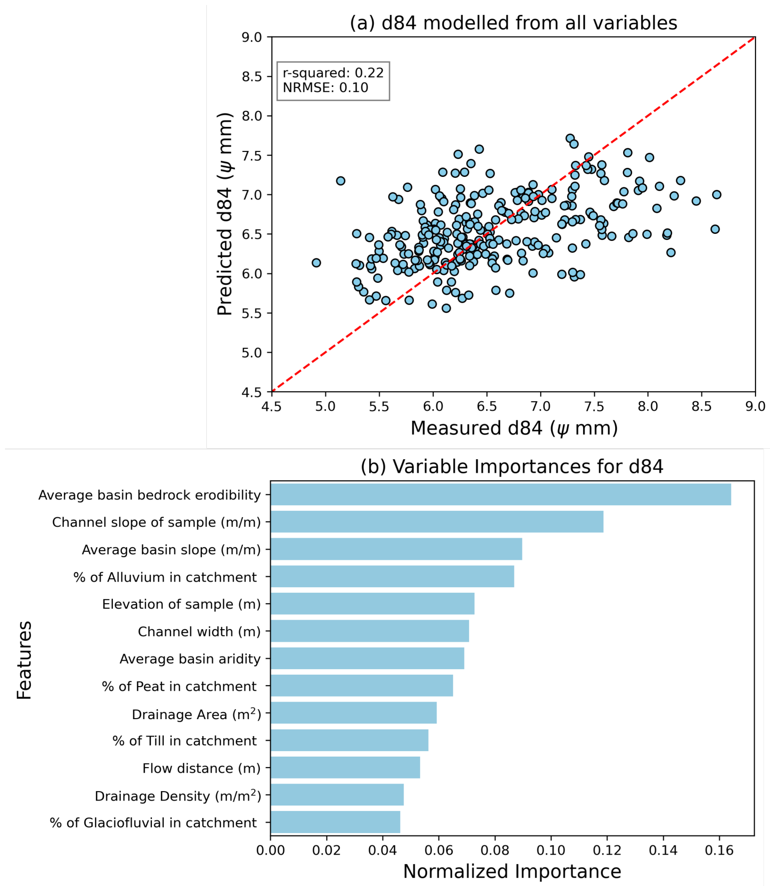

Figure 5. Results from the random forest regressor analysis. **(a)** shows the model's predictive ability, which is extremely poor. The dashed red line represents the 1:1 relationship. **(b)** shows the normalised variables' importance for predicting the d84 percentile. Normalisation is performed by dividing each importance score by the sum of all importance scores.

are also observed for the d50 and samples that have been measured manually (see Figure S4 in the Supplementary Data). We note however that ≈ 50 % of the d84 data at high flow competence ($\omega'_m > 50000$ m) sits in the lower two quartiles of the entire d84 distribution, potentially reflecting supply-limited grain size conditions (i.e., the river has the potential to transport coarser sediment but coarse sediment is not available for transport). We acknowledge that actual trends may be obscured in the noise due to the dataset amalgamating data from a very wide range of geological and geomorphological settings across Scotland. We therefore isolate the Feshie River basin which is very dynamic, with evidence of frequent bedload transport (Matthews et al., 2024) and for which we have 18 data points (Figure 6b). Similarly, we observe no apparent correlation between ω'_m and d84, although we note again that three of the four data points with the highest flow competence sit at values close to the median of the entire Feshie dataset.

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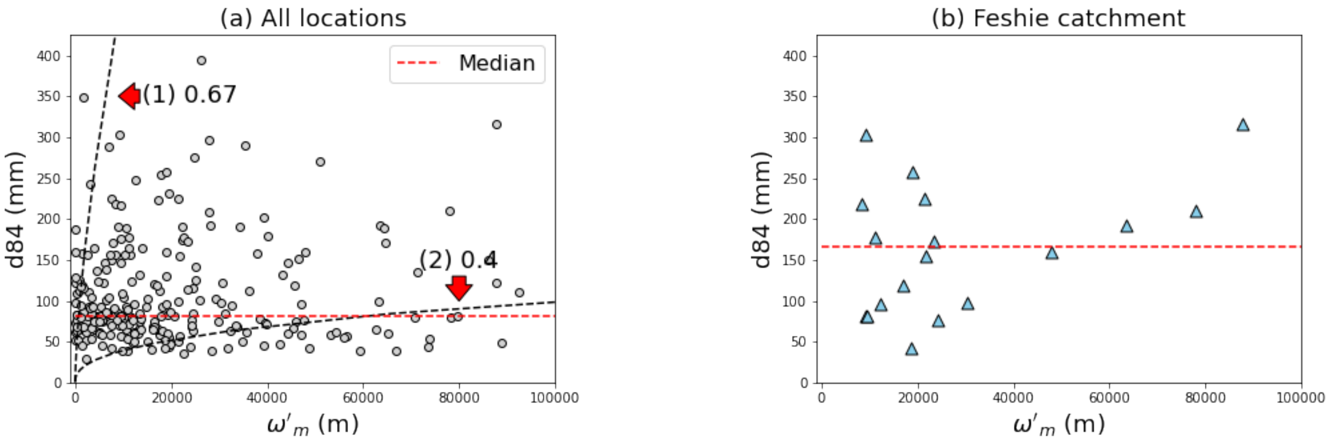

Figure 6. d84 as a function of variable ω'_m which is a proxy for flow competence (Equation 8). **(a)** shows the results for our Scotland-wide dataset. The median of the entire d84 distribution is shown by the red dashed line. Black dashed lines represent power law relationships between d84 and ω'_m with exponents of 2/3 and 0.4 (curves (1) and (2), respectively). These curves bracket the range of exponents found by Attal et al. (2015) in the Feather River basin, Sierra Nevada, California: they found exponents of 0.4, 0.53 and 0.61 best fit their data for the d100, d84 and d50 of their measured surface sediment, respectively. Median grain size d50 was fit with the exponent closest to the expected 2/3 value from experimental work and compilation of field studies (Bathurst, 2013; Whitaker and Potts, 2007). In a scenario where sediment grain size is controlled by flow competence ('transport-limited'), a power relationship between grain size and ω'_m would be expected. **(b)** shows the relationship between ω'_m and d84 for the Feshie basin which is a mountain river in the Spey catchment where 18 data points are available (see Figure 3 for the Feshie's location). The median of the Feshie's d84 distribution is shown by the red dashed line.

4 Discussion

In this study, we do not find any apparent control on surface grain sizes in channels across Scotland. Our results contrast with those of Snelder et al. (2011) and Mugodo et al. (2006) who found that grain sizes and/or substrate cover could be reasonably well predicted for rivers at large spatial scales. Snelder et al. (2011) found that grain sizes could be reasonably well predicted for rivers across France using a random forest model: in their study, the random forest predictor captured 52 percent of the variance in the measured grain sizes (sample size > 500), whereas in Scotland we find the random forest predictor only captures 22 percent of the variance of d84. Mugodo et al. (2006) found that 65 percent of the variance in fluvial substrate cover could be predicted for rivers across eastern Australia (sample size < 100). We also find no correlation between flow competence and grain size: d84 values ranging from 40-350 mm are observed across several orders of magnitude of the parameter ω'_m (Figure 6).

Scotland's post-glacial legacy may drive our inability to predict grain size based on a number of landscape properties that have been shown to control grain size elsewhere, such as gradient, underlying lithology and downstream flow distance (e.g., Attal and Lavé, 2006; Sklar et al., 2017; Snelder et al., 2011). As discussed in Section 1, past glaciations have modified the spatial locations and grain size distributions of sediment stores, and the drivers of flow competence (i.e., channel slope and width)

(Attal and Lavé, 2006; Ballantyne, 2019; Johnson et al., 2022; Mason and Polvi, 2023; Reid et al., 2022; Whitbread et al., 2015). In many Scottish river basins, channel erosion has exposed paraglacial sediment stores that contribute large quantities of sediment to modern rivers (e.g., Ballantyne, 2019). The longitudinal profiles of rivers also shows a strong glacial control that can influence sediment transport; many profiles are highly irregular, with long stretches of low gradient reaches that are interspersed by shorter, steeper reaches (Jansen et al., 2010; Whitbread et al., 2015). The empirical modelling approach applied in this study uses, in some cases, catchment-averaged variables that do not reflect spatial variations in sediment supply and transport capacity along river profiles. Studies have shown that spatial variations in the grain size of sediment supplied to rivers can significantly impact the grain size of sediments in rivers locally and further downstream (e.g., Attal and Lavé, 2006; Attal et al., 2015; Sklar et al., 2006; Whittaker, 2012). We therefore suggest that Scotland's post-glacial legacy contributes to the absence of correlation between grain size and landscape properties.

Snelder et al. (2011) found average basin slope to be the most important control on fluvial grain sizes for rivers across France. In contrast, we did not find a significant relationship between grain size and basin slope at our sampled locations. In addition to the supply of material from glacial and paraglacial sediment stores and irregularities in channel profiles, we suggest that the general decoupling between hillslopes and channels in post-glacial landscapes also contributes to such observations. Many Scottish river valleys exhibit 'U' shaped valleys with wide valley floors meaning that significant stretches of the channel network are disconnected from hillslope sediment sources (Ballantyne, 2008; Whitbread et al., 2015). Studies have suggested that in the absence of sustained tectonic uplift or base level lowering, valleys are likely to maintain their glacially inherited 'U' shaped topography and remain in a state of transient dynamics that last for millions of years (Ballantyne, 2002; Egholm et al., 2013; Prasicek et al., 2015; Whitbread et al., 2015).

While we observe no apparent relationship between flow competence and grain size in Figure 6, we find fine grain sizes across a wide range of flow competences, including high flow competences. This observation may indicate that sediment grain size is supply-limited in some rivers, that is, river stretches with high competence transport fine sediment because no coarse sediment is available for transport. Likewise, coarse grain sizes are found in rivers with relatively low flow competence. We propose that the heterogeneous nature of post-glacial sediment supply and post-glacial channel morphology contributes significantly to the supply-limited and transport-limited grain size conditions observed in the flow competence analysis. Steep, powerful rivers may source sediment from fine-grained glacial and paraglacial deposits. Likewise, rivers with a low flow competence, such as those that drain plateaus and low gradient valleys, may be locally supplied with sediment from coarse-grained glacial and paraglacial sediment sources (Figure 7). For example, the Garry River (Spey basin) has a low apparent flow competence, but exhibits some of the coarsest sediment on our Scotland-wide map (d84 = 188 mm). A potential explanation for this could be that sediments are largely sourced from the abundant upstream paraglacial and glacial deposits. These coarse deposits are only likely to become mobile during the largest of flood events. Diagrams and photographs in Figure 7 illustrate the post-glacial geomorphic processes discussed in this paragraph.

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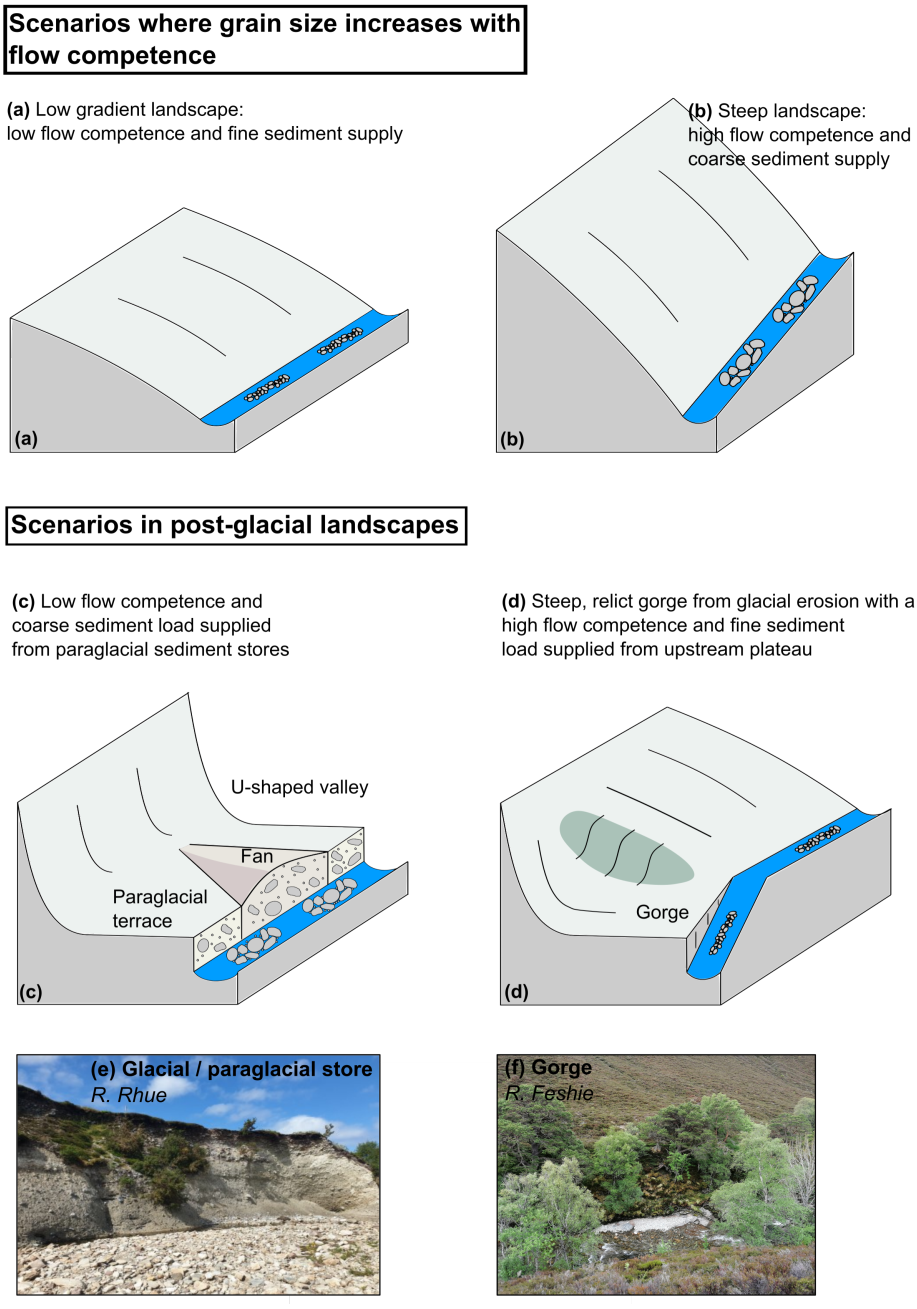

Figure 7. Caption on next page.

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Figure 7. Diagrams and photographs illustrating the contrast in sediment dynamics between non-glaciated landscapes and post-glacial landscapes. **(a-b)** In non-glaciated landscapes, feedbacks are expected between erosion rates, hillslope steepness, channel steepness, and the grain size of the sediment supplied to rivers (Attal et al., 2015). In slowly eroding, low relief landscapes, low competence rivers (low gradient) are supplied with and transport fine sediment **(a)**. As relief increases, rivers become more powerful (steeper gradient, higher competence) and are supplied with a wider range of grain sizes **(b)**. In a scenario where all grain sizes are available for transport, the grain size of the sediment mobilized by a river is expected to increase with flow competence. In this case, the grain size can be considered 'transport-limited'. **(c-f)** In post-glacial landscapes, these feedbacks do not operate anymore. **(c)** shows a channel with low flow competence (low gradient) but a coarse sediment load, which is supplied from glacial and paraglacial sediment stores. **(d)** shows a steep relict gorge from glacial erosion (e.g., gorge connecting a hanging valley) with a high flow competence (steep gradient) but a fine sediment load as no coarse sediment is available on the upstream plateau. These situations are illustrated by photographs **(e)** and **(f)**, respectively. **(e)** shows a glacial/paraglacial sediment store feeding large quantities of coarse sediment to the River Rhue (scarp is approximately 10 m high). **(f)** shows a relatively fine-grained, well-sorted gravel bar along a steep bedrock reach of the River Feshie which is a tributary of the upper Spey basin (channel is approximately 5 m wide).

In this study, we used citizen science to gather grain size data on a national scale in a relatively data-sparse country. This extensive spatial coverage enabled us to explore controls on grain sizes across a range of landscapes, allowing us to document large distributions in channel slopes, widths and other environmental variables. Documenting grain sizes at such a large spatial scale would not have been feasible using current remote sensing techniques, as these methods are labour-intensive, costly, and of limited spatial coverage. The survey was cost-effective and quick, and contributes to the growing body of research using citizen science to monitor river characteristics (e.g., Riverfly Monitoring Initiative; https://www.riverflies.org/). Importantly, the survey fostered significant public engagement due to the importance of sediment on applied matters such as flood risk and habitat value.

5 Conclusion

In this study, we document river surface grain sizes across Scotland using photographs of gravel bars. Grain sizes are extracted from the photographs through a combination of manual and automated techniques. We investigate whether grain sizes can be correlated with and predicted from a series of environmental variables (such as upstream basin slope) that have been suggested to control grain sizes in previous studies. In contrast to other studies that have primarily focused on non-glaciated landscapes, we find no apparent controls on grain sizes. We find weak Spearman's rank correlations between grain size and environmental variables. We also find that grain sizes cannot be predicted from a random forest model, in contrast to Snelder et al. (2011) who found that grain sizes could be reasonably well predicted for rivers across France. We find no correlation between flow competence and grain size.

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We propose that Scotland's post-glacial legacy drives the lack of sedimentological trends documented in this study. This interpretation aligns with other studies that have highlighted the ongoing role of the post-glacial legacy on landscape evolution in tectonically quiescent terrains, both in Scotland and globally. Key geomorphic processes in post-glacial landscapes that contribute to a decoupling between channel, catchment morphology and fluvial sediment grain size include the disconnection between hillslopes and channels in "U"-shaped valleys, presence of steep reaches at various locations along river long-profiles (and not just in the headwaters), presence of high-elevation low-relief plateaus and hanging valleys, and paraglacial and glacial sediment stores (e.g., till, fluvio-glacial terraces and fans) acting as sediment sources at many locations along rivers. Thus, steep reaches (high competence) may transport only fine sediment due to the absence of coarse sediment available for transport upstream (grain size is 'supply-limited'). Meanwhile, low gradient (low competence) reaches may source sediment from coarse-grained glacial and paraglacial deposits, leading to anomalously coarse fluvial deposits that are mobilized only during the most extreme events. As a result, surface fluvial sediment grain size cannot be predicted by a global model based on environmental variables in post-glacial landscapes. Our results suggest that studies aiming to assess the controls and importance of sediment on hazards (e.g., flood risk), habitats, and river morphology in post-glacial landscapes need to rely on the careful characterisation of upstream grain size distributions and geomorphic processes.

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Code and data availability. The code for PebbleCounts is available at https://github.com/UP-RS-ESP/PebbleCounts (Purinton and Bookhagen, 2019). The LSDTopoTools software, which was used for the topographic analysis, can be found at Mudd et al. (2023). The grain size data collected for this study can be found in the Supplementary data.

Author contributions. Funding and project design was by AHT, SMM, MA and FJC. AHT conducted the data analysis. AHT led the writing of the manuscript with contributions from MA, SMM and FJC.

Competing interests. At least one of the authors is a member of the editorial board of *Earth Surface Dynamics*.

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