How big is a boulder? Evaluating fixed and process-based definitions for boulders

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Abstract

Boulders are globally widespread and influence landscape processes across hillslopes, coasts, rivers and extra-terrestrial settings. Boulders are described as particles, sufficiently large, that the movement of an individual grain promotes substantial geomorphic change. Moving beyond this conceptual definition, however, requires a somewhat arbitrary decision of how to define a minimum boulder size. Furthermore, the implications of boulder definition on study findings are rarely considered. We compare two lower thresholds for boulder size; a fixed boulder minimum diameter (> 1 m) and a variable diameter relative to the surface grain size distribution (> 84th percentile). We consider the impact of definition on measured boulder metrics, and their association with channel and catchment characteristics across 20 boulder-bed streams in northern Sweden. We also surveyed the river managers responsible for restoring these rivers, to gain a practitioner insight on boulder size definition. Definition choice resulted in fundamental differences in boulder metrics; metrics describing the number or density of boulders were negatively correlated. Using these two studies, we explore boulder definition in earth sciences, including the application of fixed definitions and those relative to grain size or system power. We emphasise the importance of evaluating the implications of the chosen boulder size definition, and communicating the reasoning behind boulder definitions and these implications. We discuss the implication of boulder size definition choice and provide guidelines for future studies seeking a process-based definition of boulders.

Keywords: *geomorphology, landscape evolution, boulder-bed river, channel-hillslope coupling, sediment transport.*

1. INTRODUCTION

Boulders are charismatic elements of landscapes. Boulders have long held intrigue; legends have grown to describe their seemingly improbable placements, and the historical cultural importance of boulders continues today (Luigi & Motta, 2012; Górska-Zabielska et al., 2020; Pukelytė et al., 2022). Boulders are important controls on geomorphic processes across a wide range of landscapes including, rivers (e.g. Yager et al., 2007), hillslopes (e.g. Beaty, 1989; Neely & DiBiase, 2020), coasts (e.g. Naylor et al., 2016; Nakata et al., 2023), and extra-terrestrial settings (e.g. Roberts et al., 2012; Mangold et al., 2021). Boulders reveal insights into past landscape evolution (e.g. Ehlmann et al., 2008; Etienne et al., 2011) and are a widely used tool in the mitigation of geomorphic risk (Lenzi et al., 2002) and habitat restoration (Nilsson et al., 2014; Liversage & Chapman, 2018). Consequently, boulders are of great interest to environmental scientists. However, for every scientific study or landscape restoration project, a decision must be made; how large is a boulder?

Grain size is an important property of sediment. Larger grains generally require more energy to transport and, consequently, move less frequently and have a greater influence on fluid flow and surface roughness. Boulders influence sediment transport and deposition patterns, both locally and at larger scales, such as by controlling the gradient of hillslopes and rivers (Montgomery & Buffington, 1997; Glade et al., 2017). Boulders also influence biogeomorphic processes, for example by promoting the deposition of large wood in rivers (Persi et al., 2020). The influence of individual boulders on the surrounding environment is key to their definition. In a recent review on the role of boulders in landscapes, Shobe et al. (2021, p1) described boulders as particles of sufficient size that “the motion of a single grain, infrequently mobile in size-selective transport systems, constitutes or triggers significant geomorphic change”. However, grain size is a continuum and determining a threshold size is a challenge. Surprisingly, there is little consensus on how to define boulders or understanding of how this arbitrary, but necessary, decision influences study results (Shobe et al., 2021; Blair & McPherson, 1999).

Udden (1914) and subsequently, Wentworth (1922), fixed the minimum diameter for a boulder as 256 mm. Blair and McPherson (1999) and Terry & Goff (2014) maintained the 256 mm lower bound for boulders and added additional categories for coarse grains (e.g. 256 mm <boulder< 4.1 m <meso-boulder< 65.5 m <macro-boulder; Terry & Goff, 2014). Whilst the 256 mm definition is widely used within sedimentology, it is of limited use when considering the influence of boulders on landscape processes, since, in many systems 256 mm are frequently mobile (e.g. moving as bedload in rivers). It is evident that, from a process viewpoint, what constitutes a boulder varies between systems, based on system power and the site grain size distribution (GSD, Shobe et al., 2021).

Consequently, many researchers have decided that a larger minimum diameter for boulder size better captures the process-based importance of boulders (e.g. 0.5 m Nitsche et al., (2011); >1 m Keller et al., (2015); ≥2 m Nativ et al., (2022)). Minimum diameter may be based on physical processes (e.g. mobility; Keller et al., (2015)) or based on more practical constraints such as the minimum size accurately identifiable from remote sensing (e.g. > 0.3 m Finnegan et al., (2019); 0.46 m Wiener & Pasternack, (2022); 0.5 m Allemand et al., (2023)).

When comparing multiple sites, a key question is whether the definition of a boulder should stay constant or vary based on site context, such as scaling according to relative particle mobility or relative grain size (Nitsche et al., 2011; Shobe et al., 2021). Defining boulder size relative to the wider sediment distribution at a site is a widely used method in boulder studies (Shobe et al., 2021); e.g., the D_{84} (the grain size larger than 84% of grains) is often used to characterise roughness in boulder-bed streams (Schneider et al., 2015; Clancy, 2021). This recognises that the process-importance of boulders on flow and sediment dynamics varies between sites, based on the characteristics of the surrounding sediment (Shobe et al., 2021).

There is considerable variability in the definition of boulders and surprisingly little consideration of how the choice of boulder size definition may influence research results. Nitsche et al. (2011) found that varying the minimum boulder diameter from 0.5 to 0.9 m changed the modelled river bedload volume by up to 24%, based on the effect the choice had on input parameters, including mean boulder size, boulder concentration and step spacing. Consequently, the choice of boulder definition is important. Yet, it remains unclear how earth scientists should approach boulder size definition.

We aim to investigate how the choice of a fixed (>1 m) or relative to surface sediment distribution (> D_{84}) lower threshold for boulder classification affects measurements of boulder characteristics and their association with channel and catchment variables in boulder-bed streams across northern Sweden. To achieve this, we repeat analysis of 20 rivers and more than 4,700 boulders conducted by Mason & Polvi, (in press) for both size thresholds. Since boulder definitions vary not only between academic researchers, but also within applied environmental management, we couple this analysis with a survey of river managers and restoration practitioners in northern Sweden, to understand the reasoning behind their definition of boulders. We discuss the implication of boulder size definition choice and provide guidelines for future studies seeking a process-based definition of boulders.

2. METHODS

This study extends the analysis of field data collected to understand the controls on boulder-bed channel morphology in previously glaciated catchments in northern Sweden (Mason & Polvi, in press.). In these catchments, glacial legacies influence both valley geometry and reach-scale channel morphology via glacial legacy sediments in the form of large boulders (Figure 1). These streams are semi-alluvial because boulders are not reorganised by fluvial processes (in contrast to steeper, higher energy boulder-bed systems where boulders may be reorganised into jams; Church & Zimmermann, 2007), rather, the degree of boulder influences on channel morphology restricts alluvial processes (Mason & Polvi, in press; Polvi, 2021).

2.1 Field data collection

Field surveys were undertaken on twenty river reaches that had no known human modification of boulder distributions, a challenge in northern Sweden where timber floating has affected most rivers (Törnlund & Östlund, 2006). Surveys involved mapping the channel planform, cross sections, sediment size distribution and the characteristics and distribution of in-stream boulders using a total station (surveyed river length 61 – 100 m). The GSD was measured using a 200 particle, grid-by-number count of *b*-axes (Wolman 1954; Green, 2003). For more details on field methods, see Mason & Polvi (*in press*).

Boulders were surveyed according to two definitions. First, boulders were defined as all particles with a *b*-axis >1 m (B_{1m}). Second, with a minimum diameter of D_{84} (B_{D84}). However, because considering smaller particle sizes exponentially increased the number of clasts to be surveyed in the field, we used a minimum boulder size of 0.5 m in three reaches with a D_{84} < 0.5 m (highlighted in Figure 2 and discussed in section 4.2). The top (B_{top}), and the bed elevation directly upstream (B_{us}) and downstream (B_{ds}) of the boulder were measured with a total station for all boulders within the bankfull channel area.

Table 1. Boulder metrics.

Notation	Metric (units)	Description or Formula
N	Number of boulders	Number of boulders larger than the minimum size definition
D_{50}, D_{84}	50th and 84th percentile bed sediment (m)	Bed sediment size percentiles calculated from a 200 particle count
b	Diameter (m)	Mean diameter (*b-axis*) of measured boulders
BD_c	Boulder density (m^{-2})	Density of in-channel boulders
h	Boulder height (m)	Mean height of boulders above average bed elevation h= $\frac{B_{top}-(B_{us}+B_{ds})}{2}$ Where B_{top} is the elevation of boulder top, B_{us} and B_{ds} the bed elevation upstream and downstream of the boulder respectively (measured with the total station)
P	Boulder protrusion (%)	$$\mathrm{P} = 100\frac{\mathrm{h}}{b}$$ Where *h* is height and *b* is *b-axis* for each boulder. Mean calculated across all boulders for each reach
H_t/h	Relative submergence	Mean bankfull depth H_t (m) / mean height of boulders *h* (m)
A_b	Boulder coverage (%)	$$A_b = 100\left(\frac{A_{bc}}{A_p}\right)$$ Where A_{bc} is the area of channel covered by boulders and A_p channel area within bankfull
C_{long}	Long-stream boulder clustering ($100\ m^{-1}$)	Density-based clustering within ArcGIS Pro. Number of clusters within 100 m river length within the thalweg zone, Tz
C_{cross}	Cross-stream boulder clustering (%)	$$C_{cross} = 100\left(\frac{BD_{Tz}}{\mathrm{BDc}}\right)$$ Where BD_{Tz} and $\mathrm{BD_C}$ are boulder density in Tz and the channel respectively

2.2 Data analysis

Channel planforms and boulder distributions were mapped in ArcGIS Pro (Supplementary material S1). Planform area A_p (m) was calculated as the surveyed area within bankfull limits, with islands removed. Boulders were plotted by estimating their centre (B_c) as the horizontal midpoint between B_{us}) and B_{ds}. Boulders were then plotted, centered on B_c, with diameter equal to *b-axis*. From the field measurements and planform analyses, a number of boulder metrics were calculated (Table 1; Mason & Polvi, *in press.*).

To determine if boulder size definition affected boulder metrics (e.g. number, density, etc.), we calculated Pearson's correlation coefficients between metrics calculated from B_{D84} and B_{1m}. Scatter plots were visually inspected to identify non-linear trends; significance was determined at $\alpha = 0.05$ (R package corrplot; Wei and Simko, 2021). We expanded correlation analysis to consider associations between boulder metrics and characteristics of the channel reaches and their catchments. We repeated the correlation analysis for both B_{D84} and B_{1m}. To determine the effect of definitions of boulder minimum diameters on the associations between boulder metrics and channel characteristics, we calculated the difference between correlation coefficients ($\Delta r = ABS(r\_B_{1m}-r\_B_{D84})$). To determine whether differences between correlations conducted for B_{1m} and B_{D84} were significant, we used Zou's (2007) method in the R package cocor (Diedenhofen & Musch, 2015). Two-tailed Zou tests were conducted with a null hypothesis of no difference between correlations at $\alpha = 0.05$. All correlations considered dependent variables, whilst those comparing boulder metrics were non-overlapping and those comparing boulder metrics with landscape variables were overlapping since both correlations shared the same landscape variable (Diedenhofen & Musch, 2015). Statistical analyses were conducted in R (v4.1.0, R Core Team, 2021).

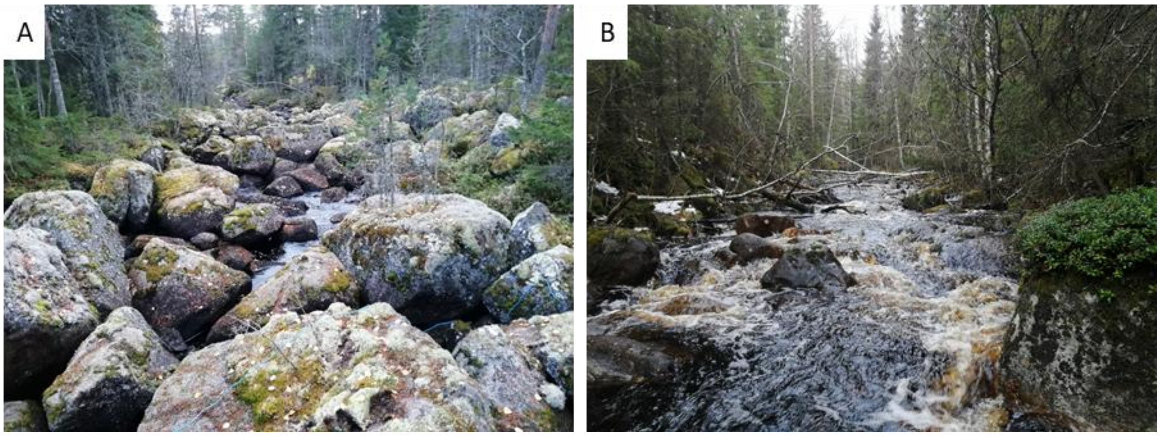


Figure 1. Two reaches at either end of the boulder influence spectrum. (A) Kuttingsån had a D_{50} of 2.31 m and the number of boulders for B_{1m} was 524 and for B_{D84} was 61. (B) Krycklan had a D_{50} of 0.1 m, 8 boulders for B_{1m} and 130 for B_{D84}. Surveyed length for both reaches was 100 m.

Table 2. Effect of boulder definition on associations between boulder metrics. Bordered cells contain Pearson correlation coefficient (r) values between boulders surveyed under B_{D84} *and* B_{1m} *definitions. Significance indicated by * (*$\alpha = 0.05$*). Remaining cells show the absolute difference between the r value obtained using* B_{1m} *and* B_{D84} (Δr). Δr *varies from 0, indicating that r values were identical, to 2, indicating the opposite correlation (i.e. perfect positive correlation versus perfect negative). * denotes a significant difference between the correlations under* B_{1m} *and* B_{D84} *(Zou (2007),* $\alpha = 0.05$). *Bold cells indicate that the direction of the correlation has changed. Shaded cells indicate that the correlation was significant for one size definition but not the other.*

		N	BD_c	P	b	H_t/h	A_b	C_{long}	C_{cross}
Number of boulders	N	0.01							
Boulder density (m^{-2})	BD_c	0.43*	-0.70*						
Boulder protrusion (%)	P	**0.87***	**1.10***	0.83*					
Boulder diameter	b	**1.07***	**1.32***	0.12	0.52*				
Relative submergence	H_t/h	0.19	0.50	0.41	0.51*	0.43			
Boulder coverage (%)	A_b	0.76*	**1.32***	0.58*	0.03	**0.51**	0.42		
Tz cluster long-stream (100 m^{-1})	C_{long}	0.34	0.22	**0.89***	**0.90***	0.35	**1.07***	-0.34	
Tz cluster cross-stream	C_{cross}	0.21	0.03	0.48	0.41	0.01	**0.64***	0.03	0.45*

3. RESULTS

3.1. Influence of boulder size definition on boulder metrics

B_{1m} and B_{D84} size resulted in fundamentally differences for boulder metrics. Whilst the number of boulders surveyed had a similar range across the sites under both definitions (8 - 524 boulders for B_{1m} compared to 42 - 534 for B_{D84}; Figure 2), there was no correlation between the number of boulders surveyed at each site (Figure 2a; Table 2). Boulder density had a strong negative correlation with a power distribution, between size definitions (Figure 2b; Table 2For the characteristics of measured boulders, mean diameter had a greater range for B_{D84} (0.67 – 2.84 m compared to 1.21 – 1.51 m for B_{1m}, Figure 2d). Mean boulder protrusion (Figure 2c; Table 2) showed a positive correlation between size definition but a greater range for B_{1m}). Boulder coverage varied considerably more for B_{1m} than B_{D84} and there was no association between the two (Figure 2f; Table 2). For boulder spatial distributions, there was a significant association for cross-stream boulder clustering measured under each definition but not for longitudinal clustering (Table 2).

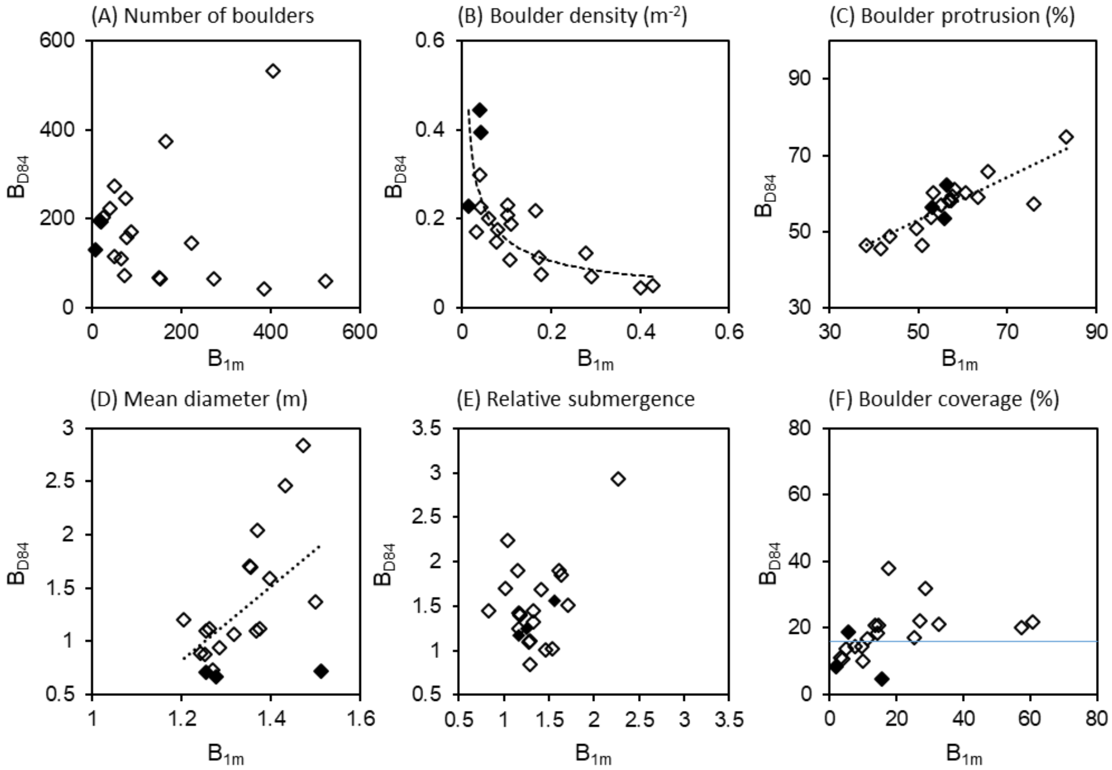
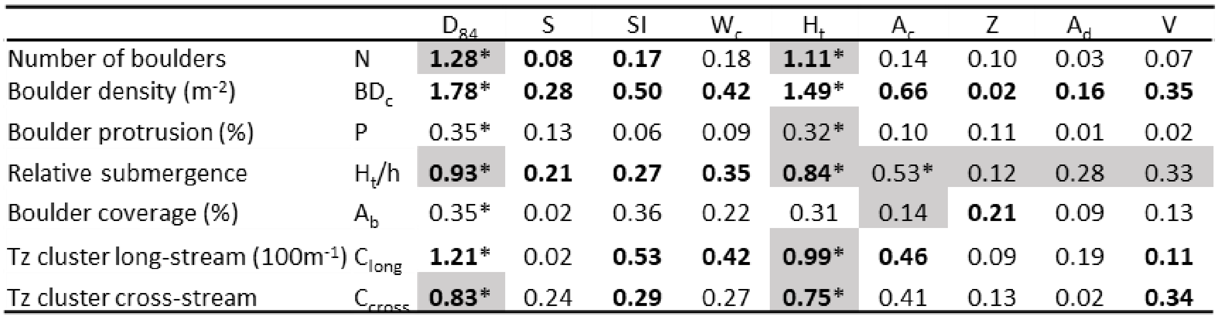


Figure 2. The influence of boulder size selection on key boulder variables. The three sites for which B_{D84} surveys were curtailed at a lower bound of 0.5 m are represented as solid symbols. Best fit trend line shown where linear correlation was significant (Pearsons, α = 0.05). On Figure F the blue line indicates 16% coverage, expected from B_{D84} calculation (see discussion 4.1).

Table 3. Effect of boulder definition choice on the association between boulder metrics and channel or catchment characteristics. Values are the absolute difference between the Pearson correlation coefficient (r) value obtained using B_{1m} *and* B_{D84} (Δr). Δr *varies from 0, indicating that r values were identical, to 2, indicating the opposite correlation (i.e. perfect positive correlation versus perfect negative). * denotes a significant difference between the correlations under* B_{1m} *and* B_{D84} *according to Zou (2007),* $\alpha = 0.05$*. Bold cells indicate that the direction of the correlation has changed. Shaded cells indicate that the correlation was significant for one size definition but not the other.*



		D_{84}	S	SI	W_c	H_t	A_c	Z	A_d	V
Number of boulders	N	**1.28***	**0.08**	**0.17**	0.18	**1.11***	0.14	0.10	0.03	0.07
Boulder density (m^{-2})	BD_c	**1.78***	**0.28**	**0.50**	**0.42**	**1.49***	**0.66**	**0.02**	**0.16**	**0.35**
Boulder protrusion (%)	P	0.35*	0.13	0.06	0.09	0.32*	0.10	0.11	0.01	0.02
Relative submergence	H_t/h	**0.93***	**0.21**	**0.27**	**0.35**	**0.84***	0.53*	0.12	0.28	0.33
Boulder coverage (%)	A_b	0.35*	0.02	0.36	0.22	0.31	0.14	**0.21**	0.09	0.13
Tz cluster long-stream ($100m^{-1}$)	C_{long}	**1.21***	0.02	**0.53**	**0.42**	**0.99***	**0.46**	0.09	0.19	**0.11**
Tz cluster cross-stream	C_{cross}	**0.83***	0.24	**0.29**	0.27	**0.75***	0.41	0.13	0.02	**0.34**

3.2. Influence of boulder size definition on the association between boulder metrics and channel characteristics

There were substantial differences in the association between boulder metrics and other channel characteristics due to boulder size definition (Table 3). Notably, correlations between all boulder metrics and surface grain size (D_{84}) differed significantly between B_{1m} and B_{D84} (Table 3). Boulder density had a strong positive correlation with D_{84} for B_{1m} but a strong negative correlation for B_{D84}, following a power trend (Figure 3a). There were also significant differences between boulder size definitions for most boulder metrics and thalweg depth (Table 3; e.g. Figure 3b). Boulder definition significantly affected the correlation between channel cross-section area and relative submergence (Figure 3f).

There was no association between most aspects of channel morphology (width, slope and sinuosity) and boulder metrics with either definition (Table 3). However, thalweg depth was associated with boulder density under both size definitions, although the strength and direction of this association varied based on boulder definition (Figure 3b). The number, protrusion and longitudinal clustering of boulders were also associated with thalweg depth for B_{1m} but not for B_{D84}. Boulder protrusion calculated using B_{1m} was significantly associated with D_{84} and boulder density (Figure 3c) but not for B_{D84}. Boulder submergence and cross-stream clustering were significantly associated with D_{84} for B_{D84} but not for B_{1m} (Table 3). Relative submergence was significantly associated with thalweg depth, channel area, elevation, drainage area and valley width for B_{1m} but not for B_{D84}.

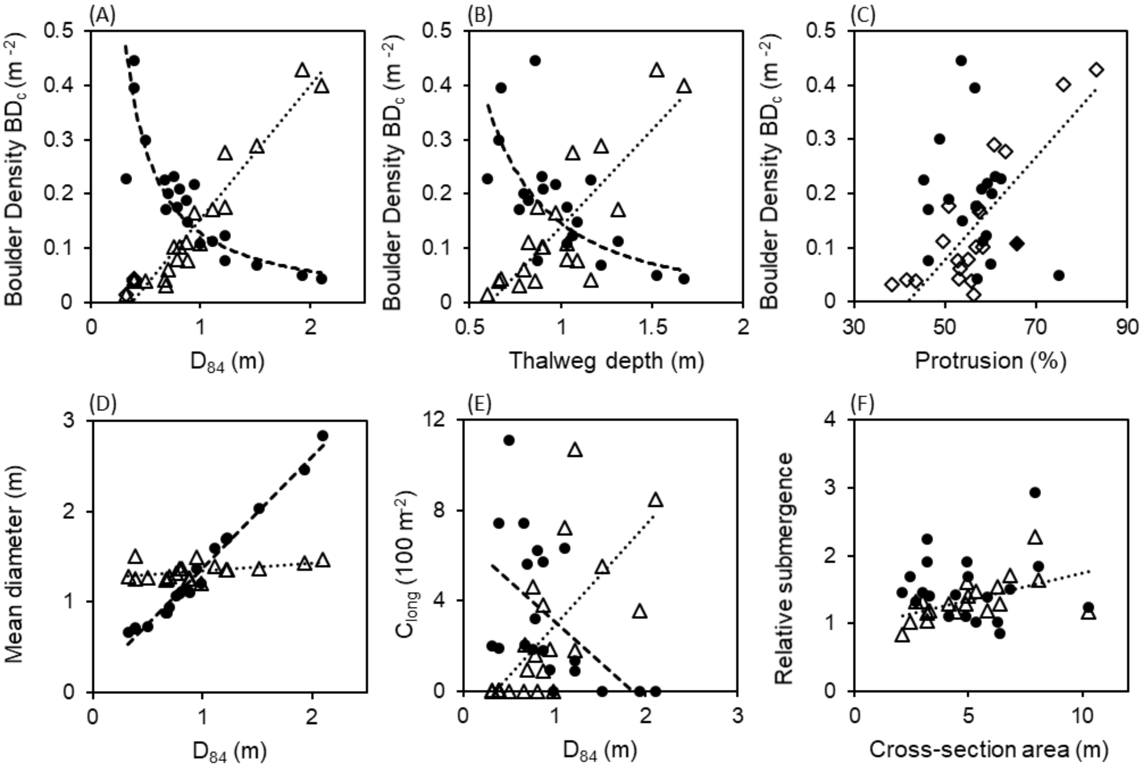


Figure 3. Influence of boulder size definition on the association between different boulder metrics and channel characteristics. Solid circles denote B_{D84}, hollow triangles, B_{1m}. Best fit trend line shown where linear correlation was significant (Pearsons, α = 0.05).

4. DISCUSSION

4.1 Fixed versus relative boulder size definitions

In our analysis, choice of a fixed (B_{1m}) versus bed sediment size scaled (B_{D84}) lower threshold for boulder diameter had important and unexpected implications. The most substantial differences related to the density of boulders in a reach, with a negative exponential association across sites between the two definitions (Figure 2b). These opposing trends can be understood by examining the method used to ascertain D_{84}; the grid-by-number approach (Wolman 1954; Green, 2003). This method provides an estimate of GSD based upon aerial coverage, since sampled points are approximately equally spaced across the riverbed (Green, 2003). Therefore, as D_{84} increases, each grain covers a larger spatial area and the density of grains >D_{84} decreases (Figure 3a). Consequently, the percentage of the river covered by B_{D84} boulders should always approximate 16% (84% of the bed surface is finer than D_{84}). This appears to be true for our results (Figure 2f, mean boulder coverage = 18%), with some scatter due to error in the estimation of D_{84} and assumptions in the calculation of boulder coverage (e.g. using *b-axis* to estimate boulder spatial coverage). This key difference between the two metrics also leads to opposing trends in metrics that incorporate, or are associated with, the density of boulders (Figure 2), including the number of boulders and longitudinal clustering. We suggest that when characterisation of the largest, most geomorphologically significant particles is required then classifying boulders relative to sediment size is appropriate. However, B_{D84} is less appropriate for comparing the degree of boulder influence across sites, since fewer particles are measured at coarser GSDs. For the latter question, a fixed definition is better suited.

The main aim of the field campaign (Mason & Polvi, in press) was to understand the relative importance of present-day fluvial controls versus glacial legacy controls (in the form of boulders) on boulder-bed river morphology. For several boulder metrics, the direction of correlations reversed making interpretation more complicated. Thalweg depth was positively associated with the density of boulders for B_{1m} which may indicate fluvial adjustment of the river to the presence of boulders (e.g. by bed degradation) but for D_{84} this association was reversed (Table 3). Similarly for protrusion, for B_{1m}, protrusion was significantly associated with variables indicating the degree of boulder influence on the channel (number, density, coverage), which may suggest that boulders promote vertical degradation in order to maintain equilibrium sediment transport (Shobe et al., 2021). However, B_{D84} boulder density decreased with D_{84} and the pattern was lost (although P was still associated with D_{84}; Table 3).

Overall, for Mason & Polvi (in press) use of a B_{D84} definition resulted in some changes in the pattern and significance of associations between boulder metrics. However, boulder and channel variables did not show self-organisation (Table 3), indicative of alluvial processes (Mason & Polvi, in press) under either definition, and therefore use of B_{D84} would not change the overall conclusions of the paper. However, at sites where fluvial re-working of boulders has occurred, these signals may be sensitive to the choice of boulder definition.

4.2 Applicability across a range of sites versus sampling effort

The definitions differed in their ability to capture boulders across the spectrum of boulder influence over the 20 sites. Studied reaches varied considerably in their GSD (Figure 1). The B_{D84} definition was better at capturing boulders at sites with lower GSD, since one reach had only eight boulders under B_{1m}. In this stream, many smaller grains were present (130 boulders > 0.5 m), which likely functioned as boulders. At the other end of the spectrum, one reach had 524 boulders under B_{1m}. The degree of boulder influence and the characteristics of these boulders could be captured without measuring all of these grains (e.g. 61 boulders measured for B_{D84}). However, at low values of D_{84}, this method was also impractical due to the exponentially large number of relatively small grains classified as boulders (Figure 3a). At three sites, sampling for B_{D84}

was curtailed at 0.5 m despite lower D_{84} (0.39, 0.39 and 0.32 m). Measurement of all boulders >D_{84} would have increased the number, density, coverage and relative submergence of boulders and decreased mean diameter (Figure 2). However, it is unlikely to have substantially affected these correlations, except to strengthen the negative exponential association between boulder densities (Figure 2b). For the purposes of this study, we do not believe that a lower cut-off in D_{84} estimation had significant consequences for the results. Instead, it emphasises the importance of considering how sampling effort is distributed between sites, since both definitions required the measurement of over 500 boulders at some reaches and only 8 (B_{1m}) or 42 (B_{D84}) at others.

4.3 How are boulders defined in applied river management?

It is evident that within academia there are many alternative methods for defining boulders (Shobe et al., 2021). To understand how boulder definition is approached by practitioners responsible for the management of rivers studied in this paper, we conducted a survey of river managers in northern Sweden. The survey was sent to employees at the county administration boards (Länsstyrelsen, Västerbotten, Norrbotten, Västernorrland, Jämtland) and townships (kommuner; Skellefteå). Survey respondents are responsible for the restoration of hundreds of kilometres of boulder-bed river, affected by timber-floating (e.g. Vindel river LIFE, ReBorn LIFE and Ecostreams for LIFE). Restoration has focussed on the addition of boulders to increase stream hydraulic and geomorphic complexity and enhance lateral connectivity. The survey is available in supplementary material S2. 15 responses were received.

Practitioners selected from multiple choices how they approached boulder definition (‘block’ in Swedish). Most used a fixed definition, which was consistent across all reaches (Figure 4a), most commonly 0.2 m (Figure 4b). Several respondents several cited sediment or habitat classification protocols (e.g. Bergquist et al., 2014; ISO 14688-1:2017). However, there was an order of magnitude difference in the size of particle classified as boulders, up to 2 m (Figure 4b). The use of 0.2 m as a minimum boulder size was surprising considering the D_{50} size of particles in these stream types varies from 0.1 up to 1.2 m (Mason & Polvi; in press). Several respondents who gave 0.2 m as a minimum diameter went on to recognise the importance of larger grains as roughness- and habitat-elements; therefore, a functional definition of a boulder may be larger. When asked to comment, several respondents mentioned functional differences between boulders and smaller particles, including grains that broke the water surface and grains of a sufficient size to “take energy from the river”. One respondent suggested a pragmatic place to draw the line between boulders and cobbles during restoration might be that boulders are strategically and individually placed, whilst smaller particles are scooped in multiples.

Whilst only one respondent indicated that their definition varied with the size of the river in question (Figure 4a), in the comments, several cited the importance of fluvial power or stream size in defining what would remain stable in the river. One respondent commented that restoration has typically been conducted in smaller streams with a lower range of sizes (e.g. 10-15 m wide). However, increasingly large rivers are being restored (e.g. 60 m wide) where a different definition is required, since a 0.2 m boulder won't have the same function in a larger river.

Ease of measurement (and visualisation) and consistency between reaches and across organisations were the most important factors influencing boulder size definitions (Figure 5). One respondent expanded to say that definition was not important, rather it was critical to be consistent between different projects. However, that said, the wide range of responses within the same or similar agencies show that practitioners may not be referring to similar grain sizes when communicating about restoration of ‘boulders’.

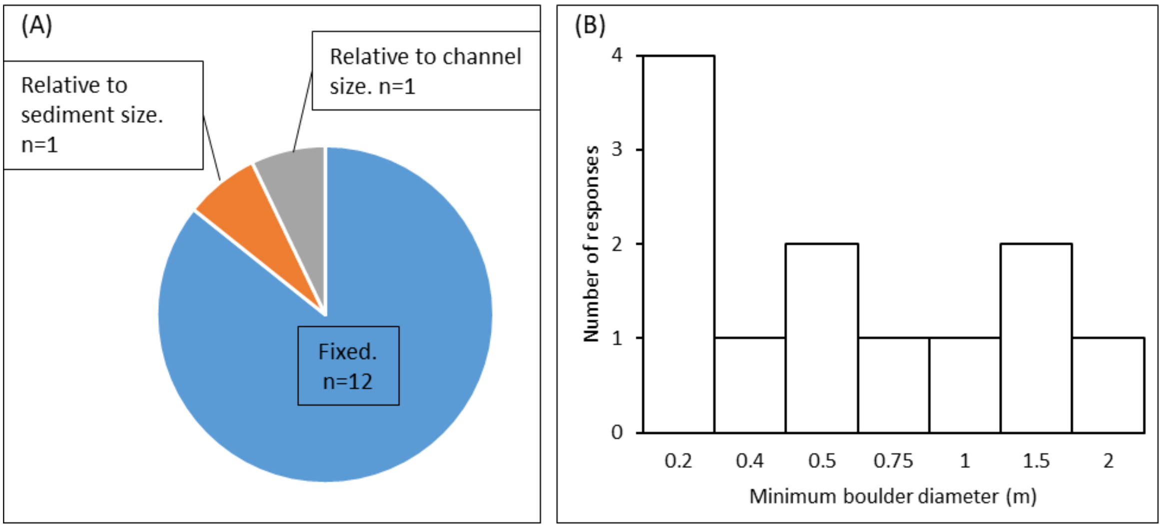


Figure 4. (A) How do you define what a boulder is when you are restoring a timber-floated stream? (B) If you selected a fixed definition, what minimum size do you classify as a boulder?

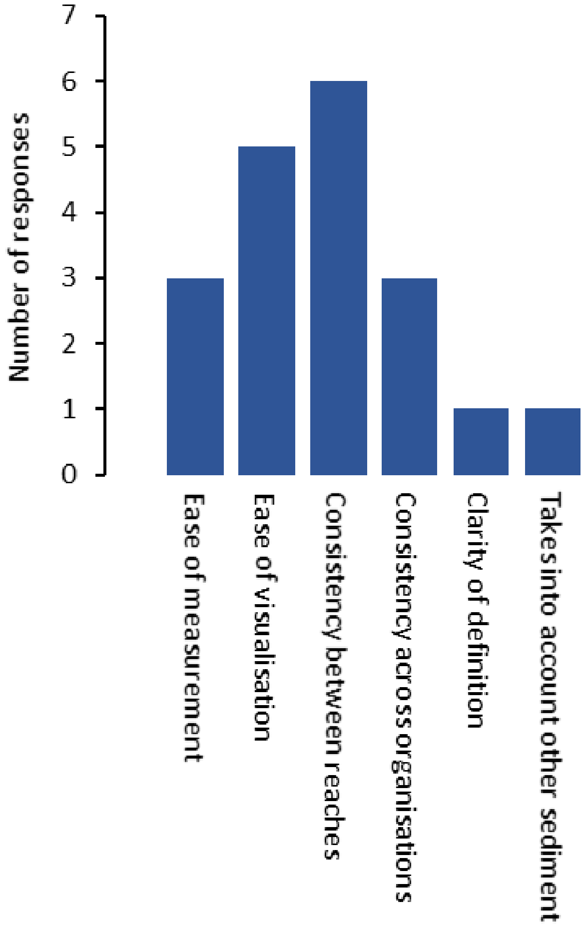


Figure 5. The reasoning behind boulder size definition indicates the importance of ease of measurement, ease of visualisation and consistency (between reaches and across organisations).

4.4 Choosing a boulder definition

The standardised size classifications (0.26 m Udden 1914; Wentworth, 1922; and 0.2 m; Bergquist et al., 2014; ISO 14688-1:2017) are well-suited where absolute particle size is of interest and provide consistency (Figure 4). However, such a definition does not take into account the wider characteristics of the system and therefore, is unhelpful and impractical as a process-based definition. We progress with the functional definition of boulders as an infrequently mobilised particle which, when entrained, constitutes significant geomorphic change (following Shobe et al., 2021).

Perhaps an ideal definition of boulder size is relative to system power. In rivers, this can be estimated from initiation of motion at a specific discharge or a flow recurrence interval based on critical Shields forces (*sensu*. Nitsche et al., 2011; Lamb et al., 2008; Keller et al., 2015; Polvi, 2021; Allemand et al., 2023). However, this definition still leaves a continuum: e.g., should a boulder be a grain that moves in the 10-or the

100-year flood? Furthermore, a thorough understanding of the potential entrainment processes is required and sometimes interest in boulder mobility may relate to historic system powers (e.g. glacial processes (Polvi, 2021), high-energy events (Greenbaum et al., 2020; Huber et al., 2020) or volcanic processes (Williams et al., 2019).

A key finding from this research is the importance of fully considering the implications of the definition (Table 4). Mason & Polvi (in press.) were interested in associations between discharge, channel morphology and boulder characteristics and therefore using discharge and slope in the definition of boulders would have been circular (Table 4). Estimations based on another characteristic of the system (e.g. GSD or stream power) are also sensitive to the reliability of that estimation. Estimation of critical entrainment thresholds for boulder influenced environments are especially challenging (Carling & Tinkler et al., 1998; Lenzi et al., 2006; Naylor et al., 2016), and errors may vary systematically between sites in relation to sediment or flow characteristics, potentially problematic for analysis.

When the process of interest is something other than relative mobility, a different measure than diameter may be more appropriate. Boulder height has been used as an alternative to D_{84} to understand the impacts of boulders on flow in rivers, since this more meaningfully captures protrusion of the grain into the flow and its hydraulic affects (Monsalve et al., 2017; Wiener & Pasternack 2022; Mason & Polvi, in press.). Dwyer et al., (2021) studied the distribution of emergent boulders since these provide essential functions for insect egg laying and emergence. Increasingly, boulders are mapped from aerial imagery (e.g. Nativ et al. 2022; Allemand et al., 2023) or 3D point clouds (Wiener & Pasternack 2022) where alternative definitions may be more practical (Table 4).

Table 4. Considerations for the choice of boulder size definition

Definition	Advantages	Challenges
256 mm	• Corresponds to standardised measurements for boulders (e.g. ISO 14688-1:2017; Terry & Goff, 2014)	• Impractical to measure all grains at sites with coarse GSD • Not functionally meaningful since at many sites these grains will move frequently
Chosen fixed size definition (e.g. B_{1m})	• Easy to interpret and visualise • Easy to measure • Can be consistent between sites • Independent of GSD and system power so suitable when associations between	• Does not take into account power of system or relative size of other particles at the site. A large grain in one system may be a small grain in another. • Can result in wide disparity in number of boulders measured between sites

	these and boulder metrics are of interest	• Typically an arbitrary cut-off
Relative to grain-size distribution (e.g. B_{D84})	• Takes into account other sediments and their role in influencing particle mobility • May be used to estimate system power (e.g. in alluvial rivers where sediment size is sorted by the river) • Relatively easy to measure • Allows focus on the largest grains (rather than having to measure all grains > a fixed cut off) • Useful as a metric of channel roughness or degree of boulder influence	• Implications for metrics of boulder number, density, coverage and diameter leading to non-intuitive associations with other river characteristics • Affected by the whole GSD so quantity of fine sediment also influences what is categorised as a boulder • Less appropriate in non-alluvial settings (where it can’t be used as a proxy for system power) or those where GSD is influenced by humans • Typically an arbitrary cut-off – what percentile of the GSD to choose?
Relative to system power	• Most appropriate definition when grain mobility is the key process of interest • Allows measurements to focus on geomorphologically important grains	• Difficult to estimate and dependent upon the reliability of this estimation • Variables used in the definition of boulder size (e.g. river discharge or slope) may affect the resulting boulder metrics • Can be complicated to define transport process (e.g. historic or present day delivery or transport process?) • Remains an arbitrary cut-off in mobility frequency
Relative to water surface (e.g. protrusion at base flow)	• Work well for specific functions (e.g. for insect emergence; Dwyer et al., 2021) • Practical for mapping from aerial imagery (e.g. Nativ et al., 2022)	• Sensitive to flow stage (challenging when comparing between sites or over time when discharge may vary) • Biased towards particles in shallow areas over those in the thalweg • Also an arbitrary cut-off

5. CONCLUSIONS

Definition of a minimum boulder size is a critical consideration in any boulder study and has implications for estimation of boulder metrics. Boulder definitions which are relative to characteristics of the system (e.g. grain size or system power) have the potential to focus sampling efforts on the most geomorphologically important grains, but need careful consideration of their influence on calculated metrics, so that variables used in the definition of boulders (e.g. sediment size or system power) are not later treated as independent variables. In our analysis, classifying boulders > D_{84} resulted in fewer boulders at coarser channel grain sizes, thus only the > 1 m definition provided a meaningful estimate of the degree of boulder influence (e.g. density or coverage) in these channels. Similar complexities could arise from scaling boulder size based on system power.

There is no one definition of boulder size, nor one preferable approach to the definition process. Instead, three considerations are important:

(1) Boulder definition should be appropriate to the project aims. This should include explicit definition of what processes are of interest (e.g. boulder mobility, stability, influence on hydraulics, sediment or biota) and the time period of interest (e.g. for rivers, contemporary typical flows (e.g. 1-10 yr), extreme flows (100 yr) or historic extremes, e.g. megafloods associated with glacial meltwater). This should guide the most appropriate boulder definition.

(2) Consider the implications of the definition for the proposed analysis. Would a different boulder definition influence the results? When comparing between sites, should boulder definition vary based on site characteristics or would this result in a circular argument?

(3) Communication of the sensitivity of results to the chosen boulder definition. In our survey of practitioners, communication and consistency were important to avoid confusion (Figure 4). This is equally true in research and we encourage future studies to evaluate how an alternative boulder metric would influence their conclusions.

Large rocks are important structural elements in landscapes, affecting hydrological, geomorphological and ecological processes. Understanding, when a large rock can be considered a boulder typically receives little justification. We hope this article will encourage earth scientists to think critically about their choice of boulder size definition.

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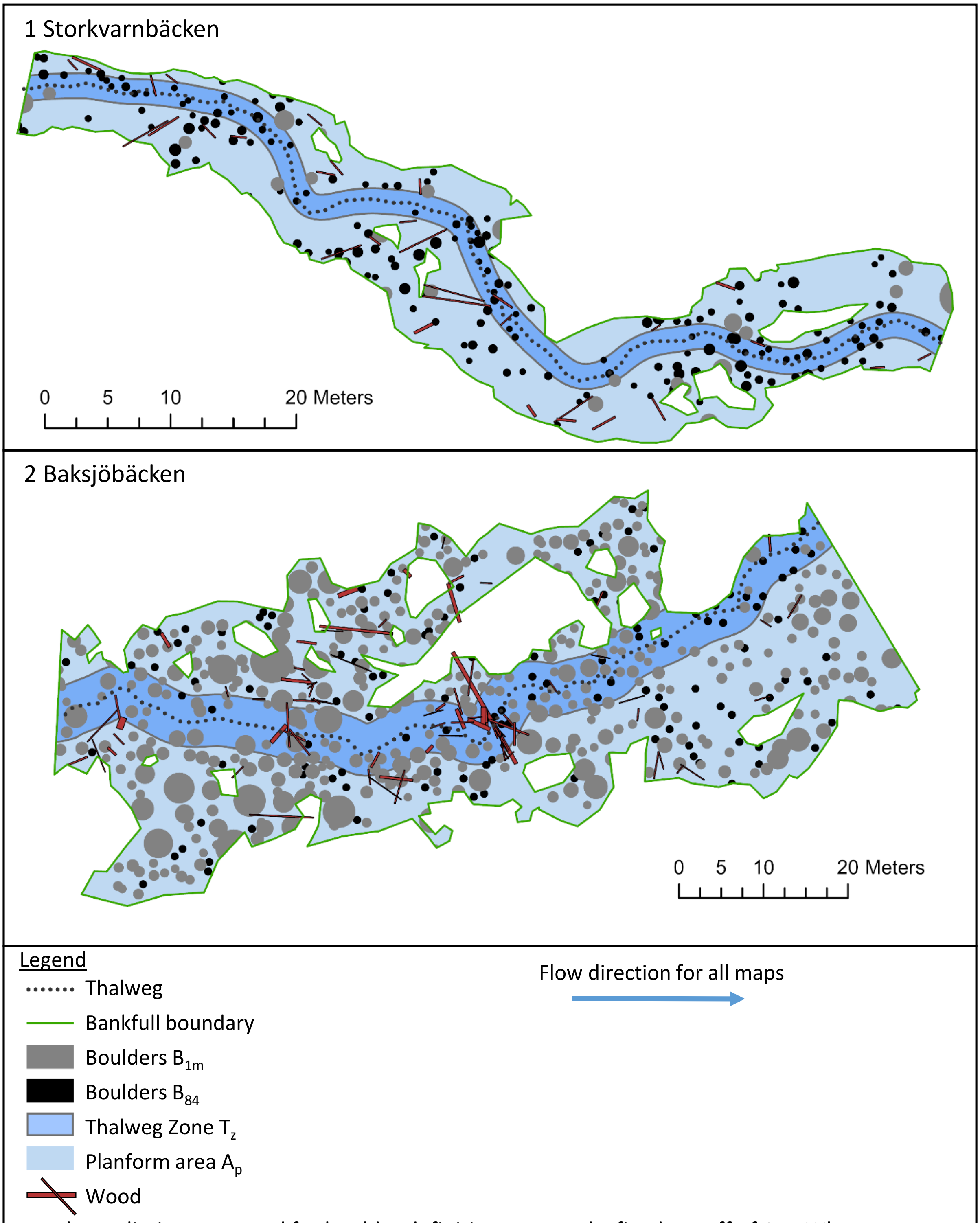
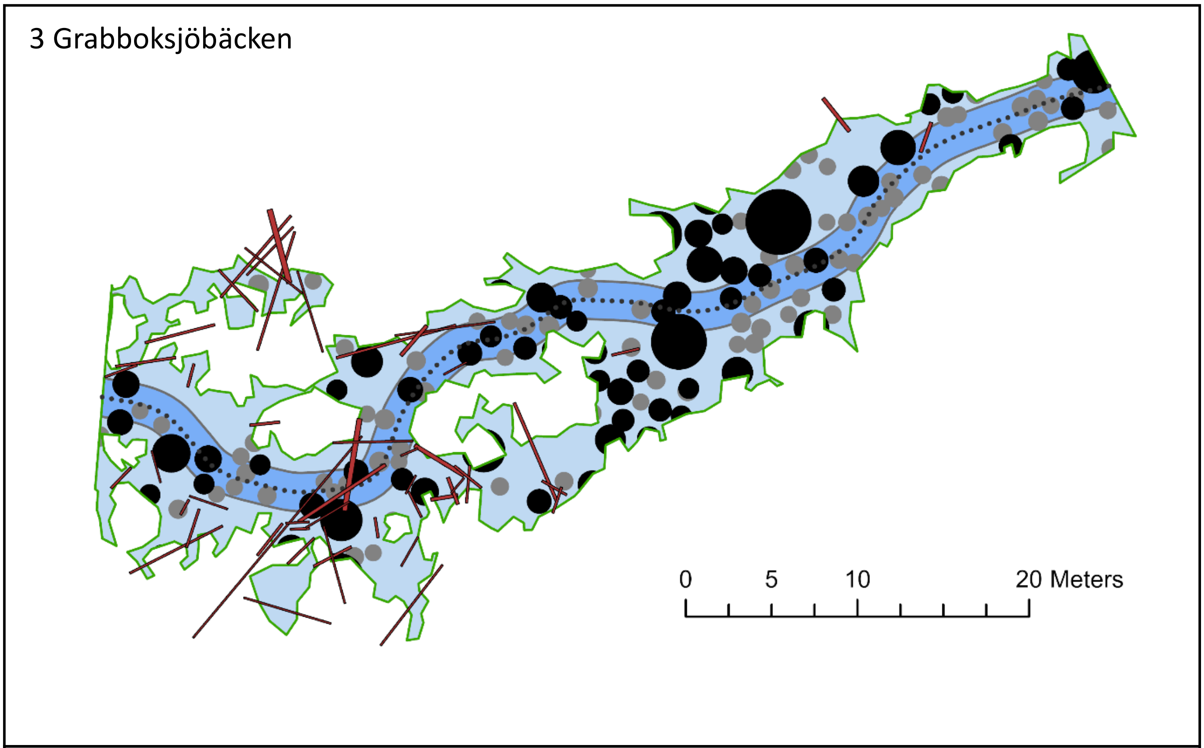
Supplementary material S1. Reach scale maps of each site.



Two lower limits were used for boulder definitions; D_{84} and a fixed cut off of 1m. Where D_{84} was less than 1m, B_{1m} are displayed over B_{84} and where D_{84} was greater than 1m, B_{84} are shown over B_{1m}, so that both are visible. Therefore the larger boulders shared by both definitions are displayed only by the boulder definition with the larger cut off. For example, in Backsjöbäcken above, all boulders are B_{84} but consideration of B_{1m} includes only those in grey.

Note that scales are unique to each map.


3 Grabboksjöbäcken
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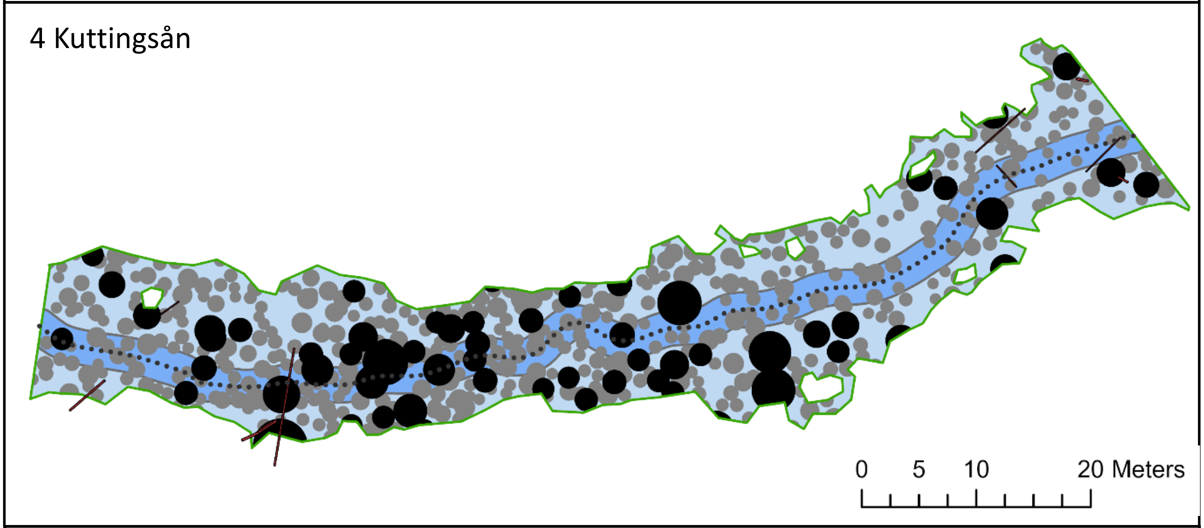
4 Kuttingsån
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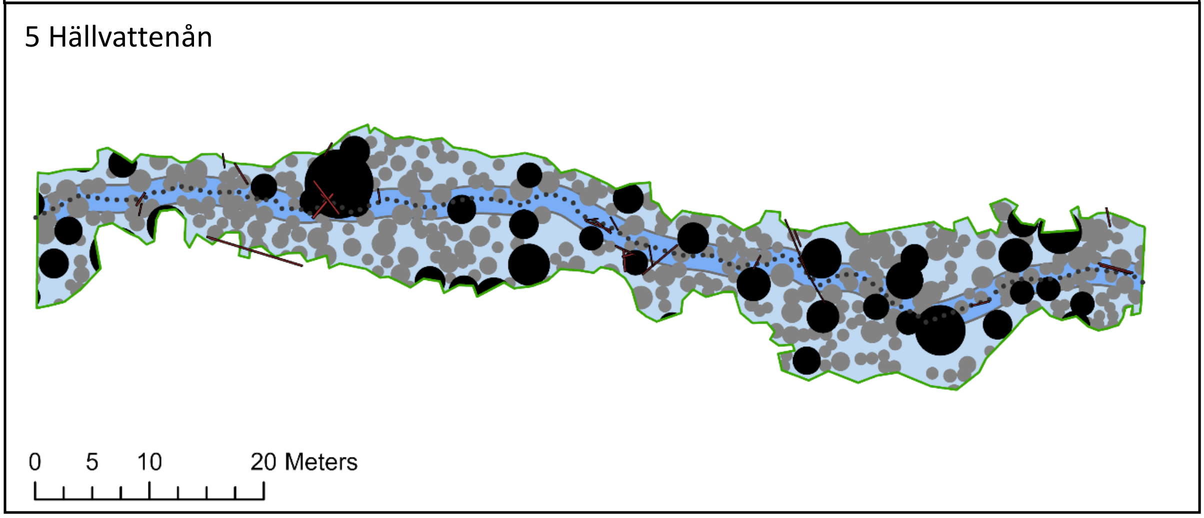
5 Hällvattenån
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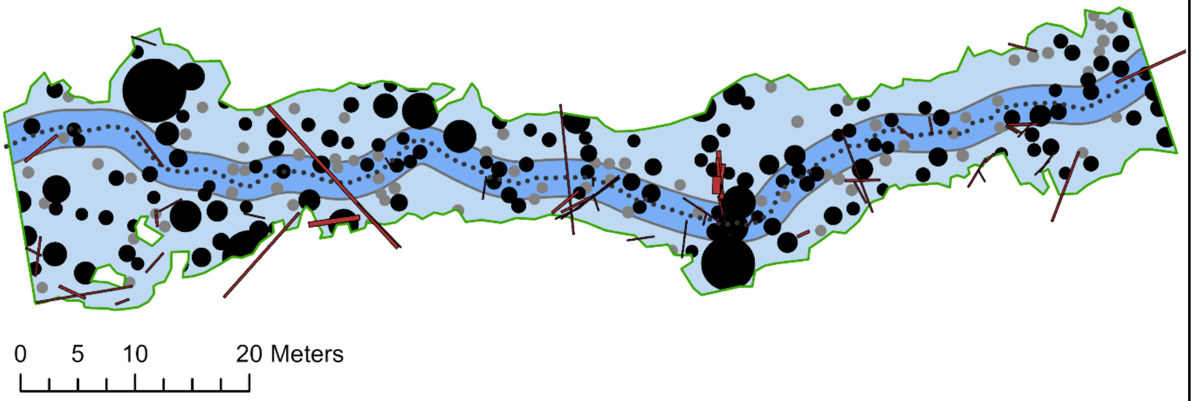
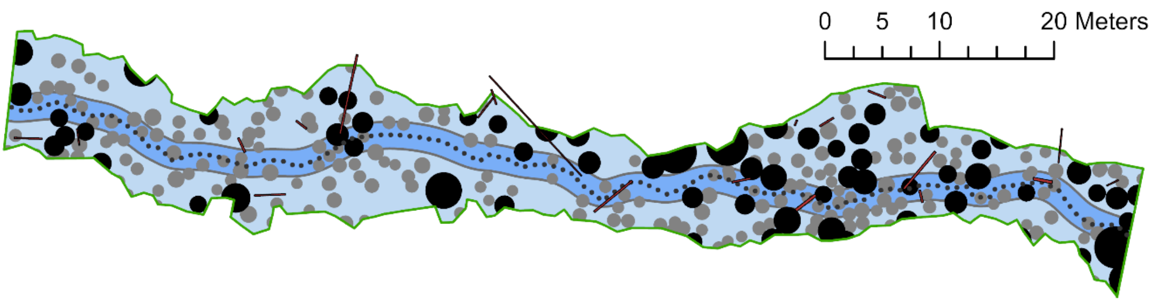
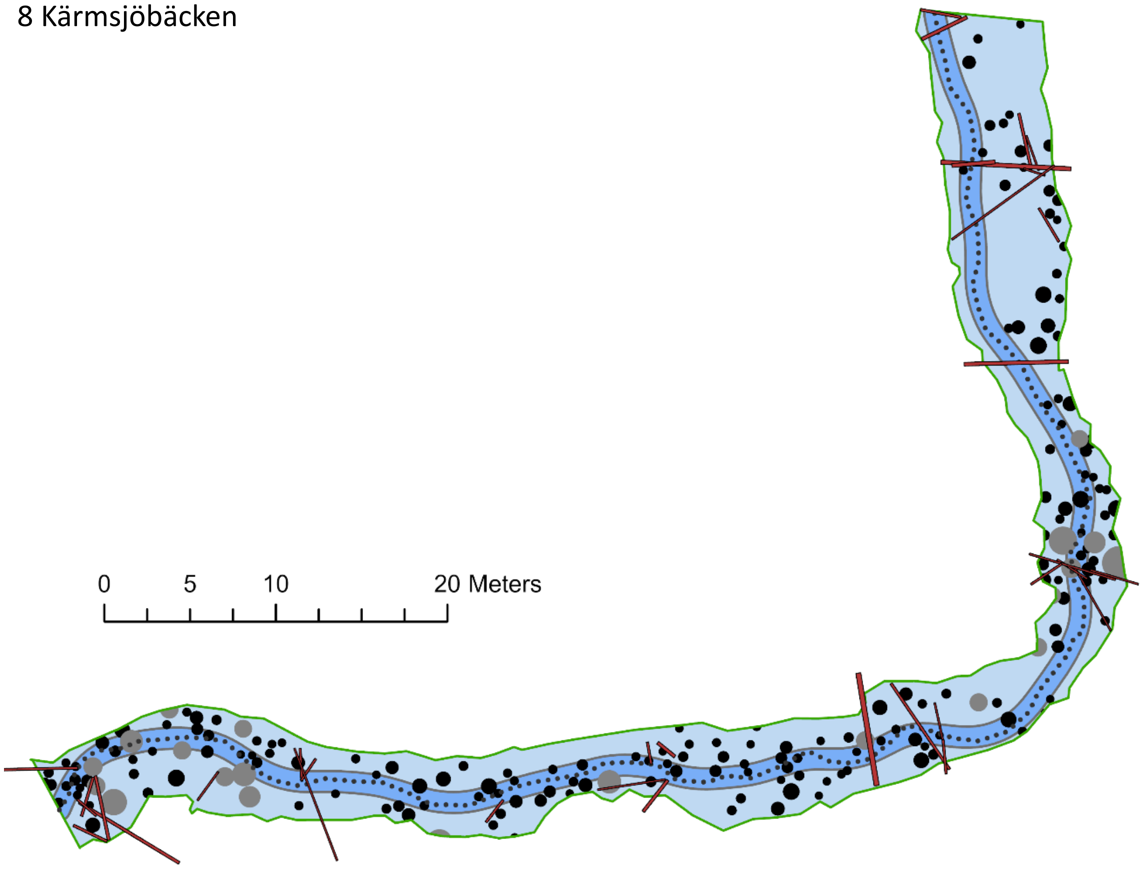
6 Länglingsån

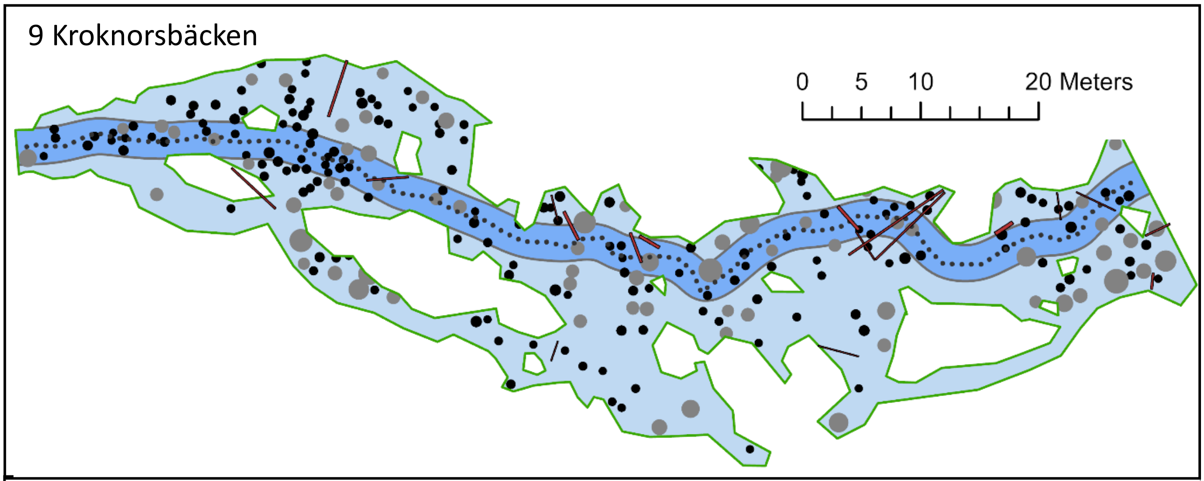


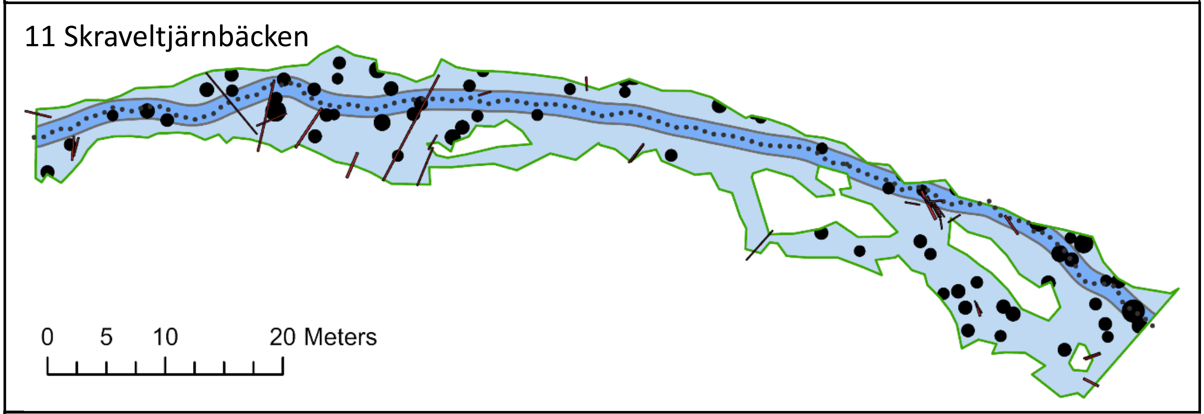
7 Harrsjöån

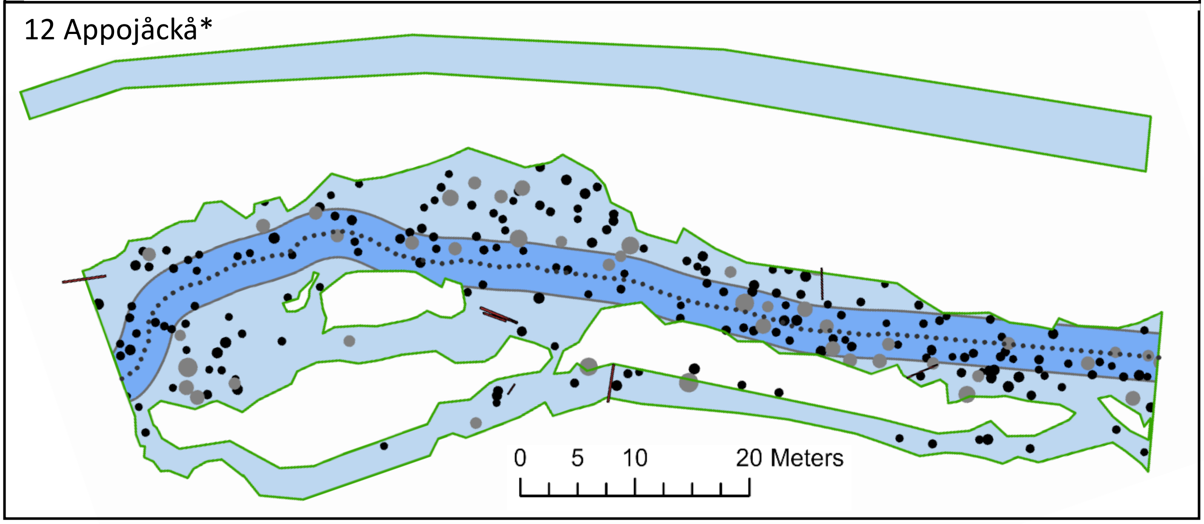


8 Kärmsjöbäcken

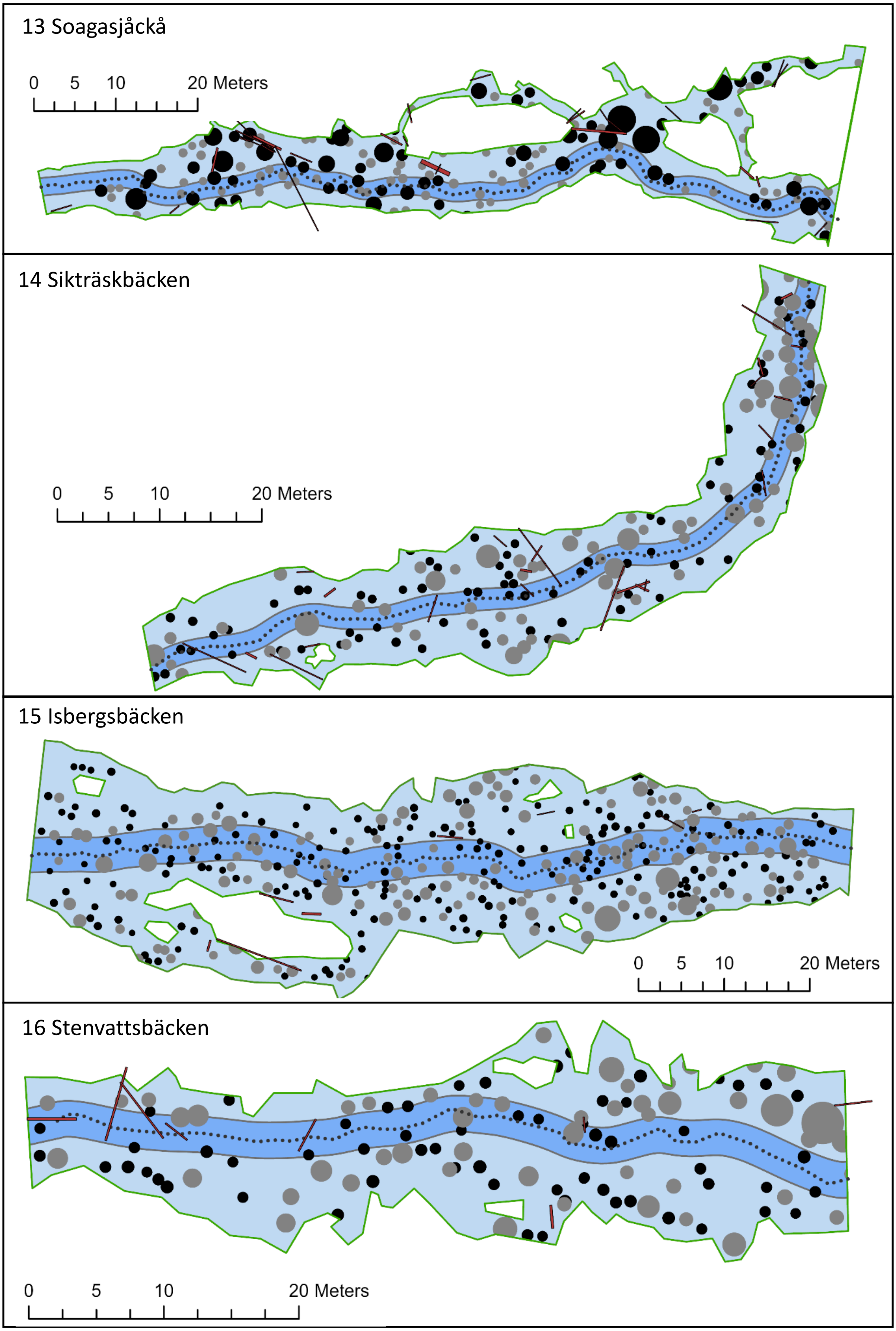








*At Appojåckå the river left side channel was separated by forest restricting survey using the total station. Several points were measured to map the channel and cross sections were measured manually. Boulders were also measured manually and were not surveyed using the total station. Therefore, variables requiring boulder distributions (e.g. boulder coverage and clustering) were only calculated for the main channel.


13 Soagasjåckå
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14 Sikträskbäcken
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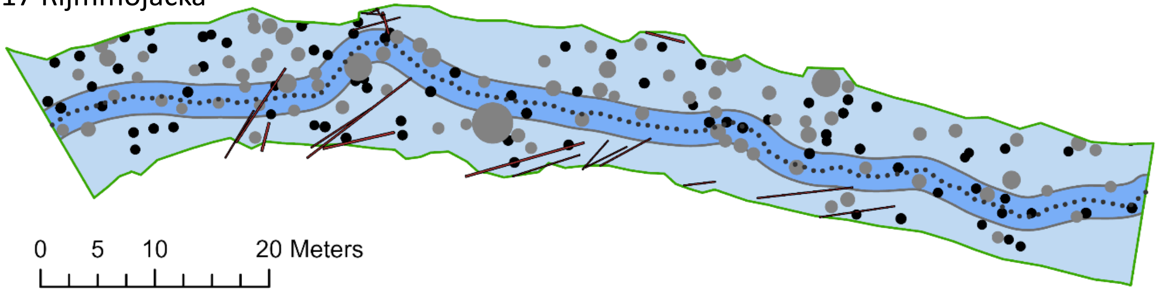
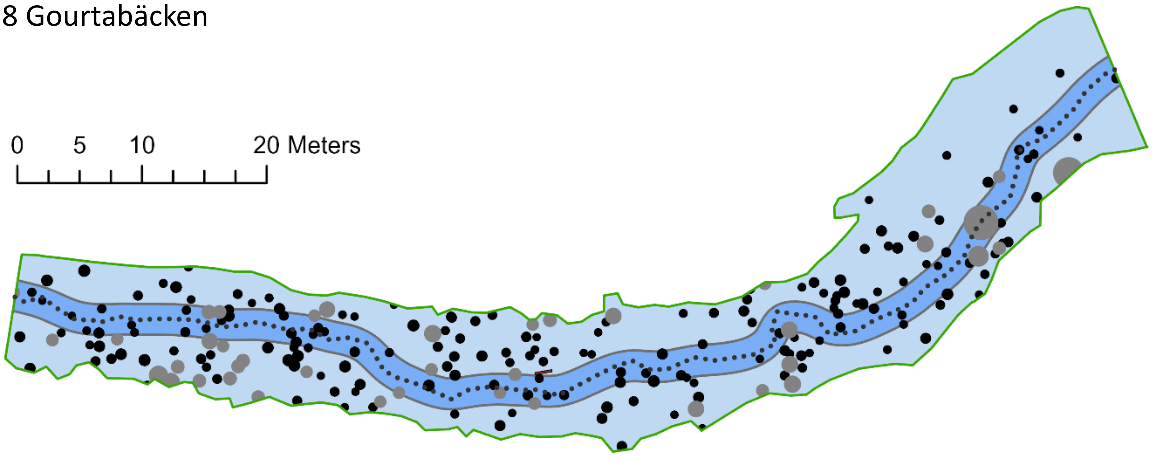
15 Isbergsbäcken
0 5 10 20 Meters
16 Stenvattsbäcken
0 5 10 20 Meters

17 Rijmmojåcka

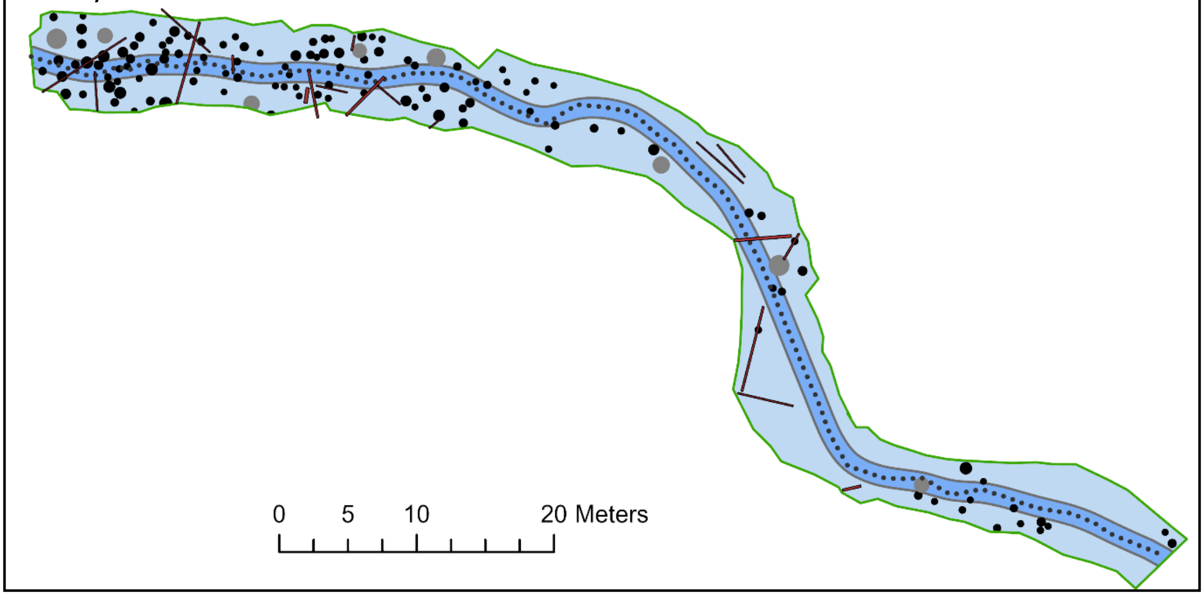


18 Gourtabäcken



19 Kortingån

20 Krycklan



Supplementary material S2. What is a boulder- survey questions
(English translation in italics)

1. Hur definierar du vad ett block är när du restaurerar ett timmerflottade vattendrag ?

   How do you define what is a boulder when you restore a timber-floated stream?

   A) Baserat på en specifik storlek av blockets diameter/omkrets (d.v.s. samma definition för alla sträckor/vattendrag)

      Based on a specific size of the boulder's diameter/perimeter (in other words, the same definition for all reaches/streams)

   B) Relativt till andra sedimentstorlekar i sträckan (d.v.s. varierar mellan fåror/sträckor beroende på sedimentstorleksfördelningen/ medelstorleken)

      Relative to other sediment sizes in the reach (in other words, it varies between channels/reaches depending on the sediment size distribution/ median grain size)

   C) Relativt till fårans storlek (t.e.x bredd eller djup) (d.v.s. varierar mellan fåror/sträckor)

      Relative to the channels size (e.g., width or depth) (in other words, it varies between channels/ reaches).

2. Om du svarade 'A' till fråga #1: Vilken storlek (diameter/bredd) använder du som minimum för att kalla något för ett 'block' (t.e.x. 0,26 m; 0,5 m; 1 m; 1.5 m; annat)?

   If you answered 'A' to question #1: Which size (diameter/width) do you use as a minimum to call something a 'boulder' (e.g., 0.26 m; 0.5 m; 1 m; 1.5 m; other)?

3. Om du svarade 'B' till fråga #1: Hur definierar du vad ett block är relativt andra sedimentstorlekar?

   If you answered 'B' to questions #1: How do you define what is a boulder relative to other sediment sizes?

4. Om du svarade 'C' till fråga #1: Hur definierar du vad ett block är relativt fårans storlek?

   If you answered 'C' to question #1: How do you define what is a boulder relative to the channel's size?

5. Välj en eller flera av alternativen nedan för att förklara varför du valde 'A', 'B' eller 'C' till fråga #1:

   Choose one or several of the alternatives below to explain why you choose ”A”, ”B”, or ”C” to question #1:

   A) Man behöver inte mäta andra partiklar
   B) Det är enklare att visualisera
   C) För att vara konsekvent i restaurering mellan arbetslag i olika sträckor
   D) För att vara konsekvent i restaurering mellan olika län, kommuner, konsultbolag, osv.
   E) För att det är viktigt att ta hänsyn till andra sedimentstorlekar i en viss sträcka
   F) För att blockhabitat varierar beroende på fåransstorlek (t.ex. 2 m vs. 100 m bredfåra)
   G) Annat

   A) One doesn't have to measure other particles
   B) It is easier to visualize
   C) In order to be consistent in restoration between work-teams in different reaches
   D) In order to be consistent in restoration among different counties, townships, consulting companies, etc…
   E) Because it is important to take into account other sediment sizes in a given reach
   F) Because boulder-habitat varies depending on the channel's size (e.g., 2 m vs. 100 m wide channel)
   G) Other

6. Har du några andra kommentarer om hur du eller din organisation definerar 'block' i restaurering av timmerflottade vattendrag? Eller vill du förtydliga något av dina svar?

   Do you have any other comments about how you or your organization defines 'boulders' in restoration of timber-floated streams? Or would you like to clarify any of your answers?