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Mathilde Morel

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Mémoire présenté pour l'obtention du diplôme d'ingénieur de l'ENGEES

Department of Ecology and Environmental Sciences

Umeå Universitet, Suède

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Pictures from Lina P.S.

DETERMINATION OF CONTROLS ON SEDIMENT TRANSPORT IN SEMI-ALLUVIAL BOULDER-BED STREAMS

SOUS LA SUPERVISION DE LINA POLVI SJÖBERG ET EMILIE BEAULIEU

MATHILDE MOREL
ENGEES – PROMOTION BRETAGNE – 2017/2020

ABSTRACT

This study aims to identify sediment transport controls in boulder-bed semi-alluvial rivers. With the emergence of river restoration projects, it is necessary to understand the mechanisms of sediment transport. Especially in these northern Sweden semi-alluvial block-bed rivers, which are still rarely studied. Tracer movement was collected over a two-year period by tracking using passive radio frequency transponders. Each tracer was associated with a class of constraint, morphology and its relative proximity to a rock. This study deals with the data relating to three sections of three different rivers.

Firstly, transport was found to be more important in the first year with at least 60% of mobile tracers and with significantly greater transport distances for unconstrained tracers for Sikträskbäcken and Isbergsbäcken, and 93.7% of mobile tracers for Mattjokkbäcken. In comparison the mobile fraction decreased of 30% except for Sikträskbäcken with almost 54% of mobile tracers. Secondly, the results for transport selectivity according to grain size did not show a clear trend in being neither linearly size selective nor equally mobile. Rather, it would appear to be a threshold diameter at which particles are less mobilizable. Morphologically, two major controls emerged: slope and boulders. Even if no clear pattern could be observed for the boulder influence, it appears to create a high variability. Moreover, the study of the critical ratio between the critical Shields parameter and the dimensionless Shields is proving to be inefficient for the prediction of movement in this type of river. Indeed, excepts for Mattjokkbäcken, at least 29% of tracers were immobile although they exceed the threshold for motion.

RESUME

Détermination des contrôles du transport sédimentaire dans des rivières semi-alluviales à lit de blocs rocheux

Cette étude vise à identifier les contrôles du transport sédimentaire dans les rivières semi-alluviales à lit de blocs rocheux. Avec l'émergence des projets de restauration des cours d'eau, il est nécessaire de comprendre les mécanismes de transport sédimentaire dans ces rivières semi-alluviales à lit de blocs, qui restent encore très peu étudiées. Des traceurs Radio Frequency IDentification (RFID) passifs ont été utilisés pour suivre la mobilité sédimentaire durant deux ans. Lors de chaque relevé des coordonnées relatives des traceurs, il a également été noté si le traceur était contraint, le type de morphologie de lit où il se trouve, ainsi que sa position relative à un rocher (en amont, en aval ou latéral à un bloc). Cette étude traite les données relatives à des tronçons de trois rivières différentes.

Premièrement le transport s'est avéré plus important la première année avec au moins 60% de traceurs mobiles et avec des distances de transport significativement plus grandes pour des traceurs non contraints pour les rivières Sikträskbäcken et Isbergsbäcken. Et 93.7% de traceurs mobiles pour Mattjokkbäcken, sans différence significative suivant la classe de contrainte. En comparaison, la deuxième année, la part mobile diminue de 30%, à l'exception de Sikträskbäcken qui conserve 54% de traceurs mobiles. Les résultats concernant la sélectivité du transport suivant la taille des grains ne montrent pas de tendance claire ni pour un transport sélectif en fonction de la taille du grain ni pour une mobilité égale. Il s'agirait plutôt d'un diamètre seuil à partir duquel les particules seraient moins mobilisables situé autour de 100mm pour l'axe B. Morphologiquement, il en ressort 2 contrôles majeurs : la pente et les blocs rocheux. Il semblerait notamment que les blocs créent une grande variabilité dans le transport sédimentaire. De plus, l'étude du rapport critique entre le paramètre de Shields critique et le Shields adimensionnalisé se révèle globalement inefficace pour la prédiction du mouvement dans ce type de rivières. En effet, mise à part pour Mattjokkbäcken, au moins 29% de traceurs sont restés immobiles bien que dépassant le seuil de mise en mouvement.

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ABBREVIATIONS

τ : Shear stress

τ^* : Dimensionless shear stress

τ_c^* : Dimensionless critical Shields stress

Cu: Uniformity Coefficient

LRS: Low Relative Regime

HFR: High Flow Submergence

H: Water depth

d_{prot} : Boulder's protrusion

Fm: Mobile Fraction

SST: Size-Selective Transport

EMT: Equal Mobility Transport

D_{50} : Grain diameter that is larger than 50% of grain

L: Transport distance

1. INTRODUCTION

1.1- Context

Fluvial geomorphic studies have historically aimed to characterize the evolution of rivers' morphologies, in particular considering sediment transport directly impacting bed texture and thus ecological habitat. (Hassan & Bradley, 2017). Progress has been made in the characterization of sediment transport particularly with the introduction of passive and active tracer particles in the field (H. Lamarre et al., 2005; Piégay et al., 2016) and through flume experiments. But considering the very unique relationship between a river and its environment inherent to each climate, historical formation, geological context, etc., there is a very wide variety of rivers (e.g. mountain rivers, alluvial rivers, semi-alluvial rivers, channelized rivers, impacted or unimpacted rivers, etc.) that would each require long-term studies to fully understand their sediment processes. Even if some common parameters can be found in different river types, e.g. boulders present in mountain rivers as well as in semi-alluvial rivers, other important parameters as the slope or the flow regime will differ. However, in a sediment transport study, the parameters inherent to the river must be taken as a whole.

According to Hassan (2017), despite the technological progresses to monitor particles, only basic features of sediment transport are generally described as travel speed and distance in field research (Hassan & Bradley, 2017). The use of flume experiments allows researchers to control the study environment and thus to determine the mechanisms behind sediment transport, characterizing the interaction with channel morphology, bed slope, and immobile features like boulders, to have a more comprehensive understanding of river evolution. (Masteller & Finnegan, 2017; A. N. (Thanos) Papanicolaou et al., 2018) In the last decades, some studies aimed to characterize the impact of boulders on the flow, shear stress and also identify patterns in sediment transport, but those studies were mostly conducted in flume, or in different rivers different from semi-alluvial rivers.

That is why there still are some gaps to fill concerning our knowledge on sediment transport in semi-alluvial rivers. This knowledge on boulders interactions on the river is important as it characterizes many semi-alluvial rivers in northern Sweden.

1.2- Semi-alluvial river characteristics

The nomenclature of semi-alluvial rivers usually refers to a river with alluvial content and a cohesive boundary meaning that the channel bed can be confined between lateral "rock walls", or the bed can be constituted by rock, constraining the channel. (Meshkova et al., 2012) But this definition can be extended to channel with immobile coarse sediment as boulders deposited by non-alluvial processes (Fig. 1).

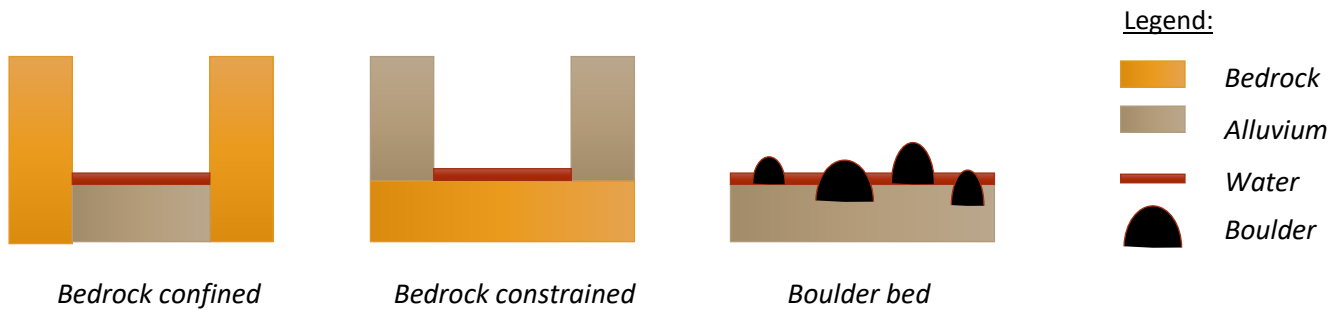


Figure 1: Different types of alluvial channels (inspired from Meshkova, 2014)

Those boulders can be a heritage from former geomorphic processes such as continental glaciation, through geological phenomena as moraines, eskers and erratic (Polvi et al., 2014). Therefore, they have a specific dynamic with the river, because boulders were not brought in by the flow, they may constitute anchor points that remain immobile even under high flow conditions depending on their size and the flow regime.

Through decades of study, a broader understanding of alluvial rivers has been reached, with a knowledge of the channel response to changes in their geomorphological parameters. (Church, 2006; Luzi, 2014) Semi alluvial sediment processes, on the other hand, have not been as intensively studied. And even if some flume and field experiments have been interested in determining patterns of sediment transport, a difference must be made based on the type of semi alluvial channel studied. A boulder-bed river will probably not experience the same processes as a semi alluvial river with a lateral cohesive boundary. Furthermore, the random distribution of boulders in different patterns in channels makes it harder to apply predictions on sediment transport from one river to another, with for example -as it will be described in the following part- different effects on hydraulic flow depending on whether it is only an isolated boulder or if it is organized in boulders arrays. (Papanicolaou et al., 2011)

1.3- Timber floating and restoration history

Historically, northern Sweden was known for the wood industry, therefore rivers had high importance as they were used to transport the wood across the country. From the mid-1800s until 1976, many rivers of the Vindel River catchment, including Mattjokkbäcken, have hence been modified to facilitate the transport of wood by removing boulders from the middle of the stream to the sides (*Vindel River LIFE*, s. d.). Smaller and steeper rivers, such as Sikträskbäcken and Isbergbäcken, were not used and therefore still remain “in a natural state”.

Since the 1970s, a desire to restore the rivers has emerged, to enhance the river ecology by increasing fish habitat and passage by injecting back coarse sediment. A recent LIFE project called Vindel River Life (*Vindel River LIFE*, s. d.) funded by the European Union in 2010, aimed to test another restoration process, taking into account the importance of boulders in those Fennoscandia semi-alluvial rivers. In addition to introducing coarse sediments and reopening streams by moving boulders from the sides of the river and the nearby forest to the center of the channel (Polvi et al., 2014). The idea was to create more heterogeneity in the stream to increase biodiversity. But as the effect of boulders is not fully understood, this restoration remains experimental.

Since the end of the The Vindel River LIFE project in 2015, studies have focused on measuring the impact of restoration by comparing the morphological complexity of rivers before and after restoration. (Hellström et al., 2019; Nilsson et al., 2017; Polvi et al., 2014) Indeed, the idea behind it is that the more complex the stream morphology, the more diverse the existing ecology will be, because the habitat is diversified. The main conclusion is that even if no significant effects have yet been observed, it should not be forgotten that ecological processes take time to establish themselves and therefore it will be necessary to give priority to monitoring over time in order to really assess the effects of these restorations.

It appears that the effects on ecology are mainly seen during winter as it for example can facilitate the formation of anchor ice, used by some species (Huusko et al., 2007). Also, studies showed that salmonids use boulders as shelters during the winter.

Quantifying the results is important to improve the next restoration method but understanding the sediment transport processes behind semi-alluvial boulder-bed rivers could significantly reduce the uncertainty of the restoration process which has been since now more an experimental and random method of boulders placement. The following part will introduce the knowledge of sediment transport mechanisms over decades of studies to present the state of the art in the matter of boulder-bed rivers.

1.4- Geomorphological control over sediment transport

1.4.1- CHANNEL AND BEDFORM MORPHOLOGY

Sediment transport has broadly been studied through a balance of driving and resistance forces (Fig.2) to establish an incipient movement threshold, called critical Shields stress (τ_c^*). From this, different parameters can be identified as controlling the sediment transport : the stream velocity, the slope in relation to the force of gravity, the density and the height of protrusion in the stream creating drag force, the size and shape of the grain on which latter forces will apply as well as friction and lift forces.

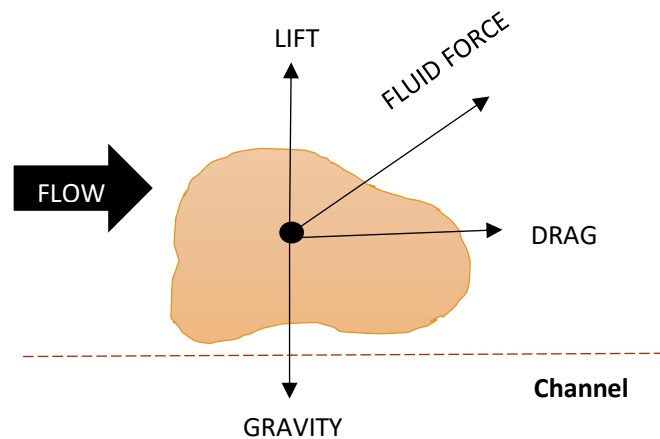


Figure 2: Forces exerted on a particle (from Ro Charlton, 2007)

- **River's global morphology :**

Within a reach, a river can have an alternation of different global morphologies as step-pool formation, riffles, plane-bed, boulder circle, which especially impact the water depth hence the hydraulic regime which will in turn influence the sediment transport. Even if precisely quantify the impact of river morphology on the river is still difficult -considering that the process creating global morphology is sediment transport which in turn will be influenced by the morphology-, many studies have proved the control of channel morphology over sediment transport and even tried to estimate it. (Hassan et al., 2005; H el ene Lamarre & Roy, 2008; Papangelakis & Hassan, 2016) Buffington & Montgomery classified rivers according to their geomorphic attributes (Buffington & Montgomery, 2013), from this and with regard to the morphologies present in this study, the following formations can be defined:

- Step-pool: A river step characterizes a slope break in the riverbed. The local hydraulic velocity is greater than directly upstream and downstream; thus, it is a morphological

structure with high transport capacities for generally cobble and sand-sized particles. A pool is a morphology where the flow velocity will decrease and the energy dissipates.

- Riffle-pool: Riffles are formed in shallow areas, usually containing coarser material. Whereas pools are deeper and calmer. The bed-shear stress in pools is higher than in riffles because of the coarser sediments, increasing the local bed resistance.
- Plane-bed: This morphology is defined as having a featureless bed structure.

- **Slope:**

The effect of slope on sediment stability can be seen in two ways. First, it is logical to think that a steep slope creates a greater imbalance in the sediment by increasing the force of gravity. But on the other hand, Lamb (2008) has shown that the critical Shields stress is positively correlated to the slope, so a steeper slope would lead to a higher critical Shields stress and thus require a higher force to set the particle in motion. (Lamb et al., 2008)

- **Boulders:**

From a hydraulic point of view, an isolated boulder protrusion represents an obstacle for the flow hence it will generate perturbation. A fully immersed boulder will create a deceleration upstream in the near-bed flow and will induce a backwater movement directly downstream the boulder called “near-wake”, finally a “far-wake” deceleration can be observed (Shamloo et al., 2001). It has been demonstrated that boulders bear a significant part of the bed shear stress through drag forces. (Yager et al., 2007) The arrangement of boulders in space has great importance in sediment transport, and lead to different hydraulic perturbations depending on their distribution in the river and their protrusion. A boulder array will imply more complex hydraulic influence, according to their repartition.

Another important parameter when studying boulders’ influence is the relative depth H/d_{prot} where H is the depth and d_{prot} the boulders’ protrusion height (Papanicolaou & Kramer, 2006; Shamloo et al., 2001). Shamloo et al. (2001) identified four different regimes depending on this relative depth (Fig.3), but in practice studies have been focusing only on the Low Relative Submergence (LRS) occurring during low flow episodes where H/d_{prot} is less than one ($H/d_{prot} < 1$). In this configuration, boulder protrudes above the water level and creates a strong backwater regime behind the obstacle.

And on the contrary, the High Flow Submergence (HRS) where H/d_{prot} is greater than three ($H/d_{prot} > 3$) occurs in high flow conditions in our case when the snow melts in spring. (Papanicolaou et al., 2018) In this case, the boulders do not impact the surface water but still create a vortex directly behind it.

These different submergence regime lead to different eddy structures, with more backwater at LRS than at HRS. An increase of bed shear stress around the boulder was also noticed (Shamloo et al., 2001). Furthermore, Monsalve (2017) demonstrated that in mountain rivers, for a low submergence level, the reach-average shear stress did not depend on depth or slope as commonly assumed but rather on the relative submergence of boulders. (Monsalve et al., 2017)

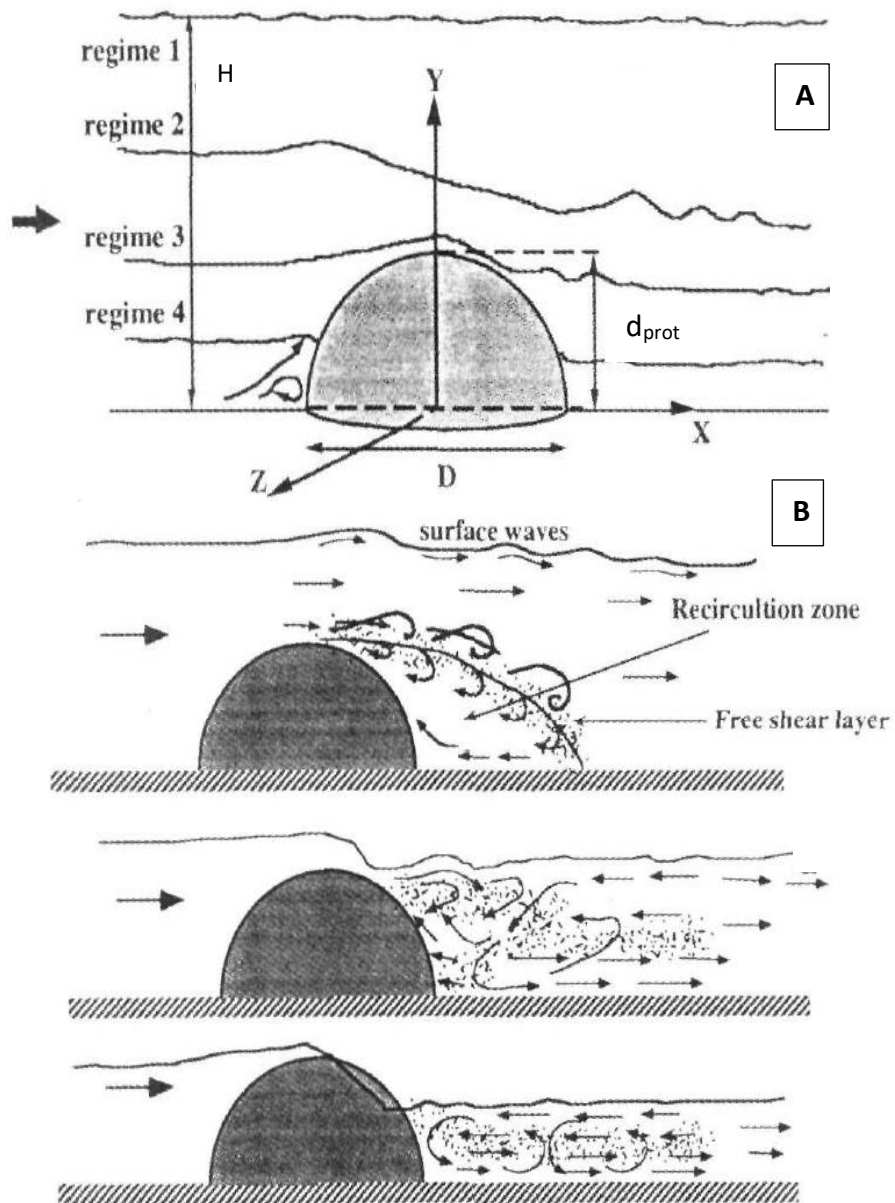


Figure 3: Flow regimes in the vicinity of a boulder (after Shamloo et al., 2001), A shows the different flow regimes around an isolated boulder, B shows the eddy structures for regime 2 to 4 (from the top to bottom)

1.4.2- ASSESSMENT OF GRAIN SIZE INFLUENCE ON THE TRANSPORT DISTANCE

Years of research aimed to find a correlation between transport and sediment size and shapes (Charlton, 2007). Figure 2 provides a good understanding of the importance of grain size because each force applied to a particle is necessarily related to the grain's attributes.

To complete the representation of forces in Fig. 2, it is interesting to represent the grain no longer as an isolated particle on the riverbed but rather as an integrated element in a heterogeneous set of sediments and structures. From there, it is then easy to imagine the interactions between different sediments of different sizes, these different types of constraint will be used in the study as classes of constraint (Fig. 4). For instance, when a larger grain sheltered a smaller one, hiding them from the flow, it induces a shielding effect, decreasing the action of the flow on the grain. An imbrication pattern can also occur when the flow deposits sediment packed together making them harder to be mobilized. When the grain is to some extent characterized by a partial burial in the riverbed, the arrangement is called embeddedness and when the grains are totally under the riverbed surface, it is defined as buried. The latter configurations would logically decrease the mobility of the grain. Finally, smaller grains can experience entrainment driven by the movement of another larger sediment.

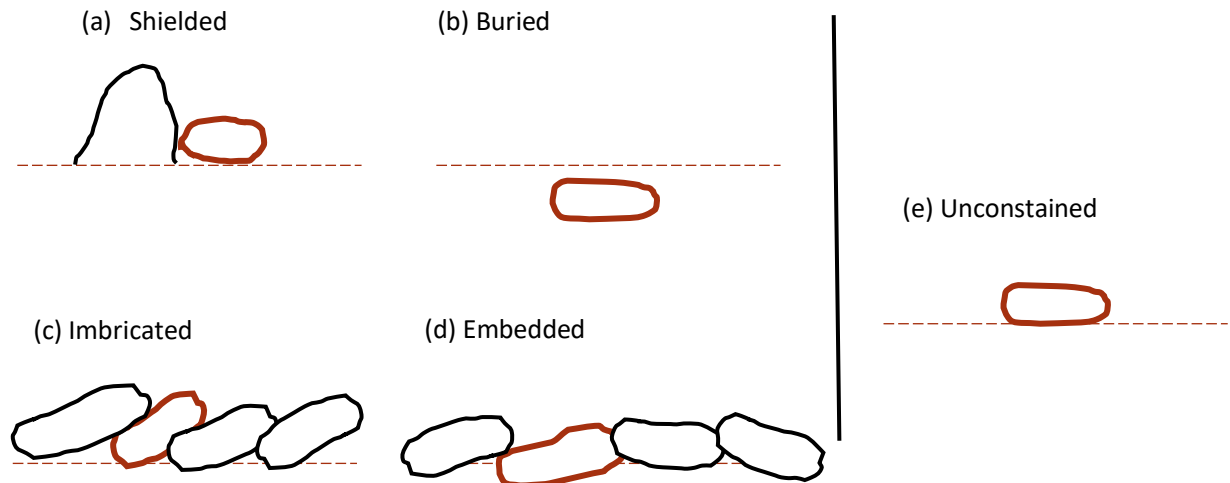


Figure 4: Schematic representation of different constraint classes of sediments used in this study; with constrained classes from a to d compared to unconstrained sediment (e)

Over the years, two main ideas concerning the control of grains' size in sediment transport were introduced:

- the Size-Selective Transport (SST): presented by Shields, this theory correlates the bed load size to the different displacement forces as for example shear stress. (Shields, 1936)

- the Equal Mobility Transport (EMT): this approach suggests that the incipient motion of a particle is not dependent on its size.

Thus, we have:

$$\tau_c^* = \tau_{50}^* \times \left(\frac{D_i}{D_{50}}\right)^{-w} \quad (1)$$

With w the hiding factor. This implies that when w is close to 1, there is size equal mobility because $\tau_c^* D_i = \tau_{50}^* D_{50}$ and thus the behavior of a particle of diameter D_i would be comparable to that of a particle of diameter D_{50} . And on the contrary, SST when w decreases. Furthermore, it can be assumed that high excess stress and transport rates, EMT is met. While SST would most likely occur when the stresses are below the threshold for entrainment (Lenzi et al., 1999).

1.4.3- SHIELDS STRESS CALCULATION STATE OF THE ART

Since the beginning of sediment studies, the main stake was finding a threshold of sediment incipient movement. This threshold is represented by the parameter called non-dimensional critical Shields stress (τ_c^*). Historically Shields suggested a value $\tau_c^* = 0.06$, but considering the wide diversity of river types with different hydraulic regimes, bed types, etc., it seems impossible to have a single representative threshold. Moreover, some authors found out other threshold values as it will be developed in later. Even if this fixed value provides a first idea of the movement, the challenge now is to have the most representative threshold as possible in relation to the geodynamic characteristics of the river under study.

A first approach consists in calculating the balance of forces exerted on the particles as explained in the previous part. But this method still omits the entire particles' interactions with the bed, because it does not take into account the interaction with other particles (as introduced in the section 1.4.2) including for example the shielding effect and more or less deep burial in the bed (Elwyn M. Yager et al., 2018) and yet the latter have significant control over particles. Yager (2018), proposed then to introduced the protrusion (p) and the effect of intergranular friction. They determined that neglecting those two parameters lead to significantly underestimate the critical Shields stress and thus overestimate the sediment transport. This study aiming to include the effect of friction in the equation is still very new but an increasing interest in more precise and diverse sediment study can be observed through literature.

1.5- Aims of the study

As part of the MorphoRest study -monitoring 5 different reaches tributaries of the Vindel and Ume Rivers-, my internship aims to have a comprehensive understanding of the sediment transport of those semi-alluvial-boulder-bed rivers with a high boulder density to provide proper guidelines for river restoration. Focusing on the study of 3 different river reaches, two unimpacted by the wood industry: Sikträskbäcken and Isbergsbäcken and one which was subjected to basic restoration in 2003: Mattjokkbäcken. Considering that the semi-alluvial rivers and especially Fennoscandia rivers are still

very little studied and knowing yet the importance of boulders in a river, it is essential to be interested in the sedimentary mechanisms that act on these rivers. Especially in the current context inclined to the restoration of rivers. Indeed, those restoration measures aim to reproduce the former morphology of the rivers by reintroducing boulders in the middle of the river, but the process is still very experimental with a random repartition of boulders.

To determine the major control factors over sediment transport, some hypothesis were emitted:

- Results should be different from the first year to the second one because of the “unnatural” input of tracers the first year
- The transport depends directly on the grain size and the slope, higher grain size would require higher shear stress, higher slope implies higher critical Shields stress
- Unconstrained sediment will have a higher transport distance than constrained ones
- Grains in the vicinity of boulders (closer than 1-2m) will have a smaller transport distance compared to the ones further
- A different pattern will be observable according to the relative position of the grains upstream or downstream a boulder
- Step morphology will induce greater transport distance

2- MATERIAL AND METHODS

2.1- Study site

The three reaches are located in a subarctic climatic region in Västerbotten County in northern Sweden, Sikträskbäcken is tributary to the Ume River and Mattjokkbäcken and Isbergsbäcken are tributaries to the Vindel River (Fig.6). Both rivers start in the Scandinavian mountains flowing South-East, to merge 40km from the Gulf of Bothnia. With a total basin area of 26,815km², this catchment is the fourth largest watershed of Sweden. (*Ume- och Vindelälvens Vattenvårdsförbund*, s. d.)

The tributary rivers to the Ume and Vindel Rivers are often connected and buffered by lakes (as Fig. 6, B); for example over the 12,654km² representing the Vindel river catchment, 5% are occupied by lakes (Nilsson et al., 2017). Those lakes can act as hydrological buffers, limiting the flood peaks in spring. The three reaches are exposed to an extreme winter season with snowfall from November to April and ice cover on rivers and lakes. From an ecological point of view, the rivers are surrounded by coniferous forests and the majority of fish species are brown trout, Atlantic salmon, bullhead, pike, minnow, burbot and European grayling (Palm, 2007).

The maximal discharges are driven by snowmelt during the spring. The precipitations in the region range from 500 to 850 mm per year. The mean annual air temperature is between 2-4°C, and reaches its maximal mean monthly temperature during July with 10 to 15°C and its lowest temperature in January with -9 to -15°C. (Nilsson et al., 2017)

The study area is located above the formerly higher coastline which separates the land that emerged with postglacial isostatic rebound and the former glaciated areas. (Lambeck et al., 1998), thus the area was not exposed to coastal deltaic processes but rather to glacial processes as explained before. Continental glaciation induced the transport of large boulders, that are now anchor points in these rivers. (Polvi et al., 2014)

Sikträskbäcken and Isbergsbäcken are so-called “natural” rivers as they were not impacted by timber floating because of their width and slope. Which is not the case for Mattjokkbäcken, which was successively used for the wood industry and then restored by placing back boulders in the middle of the stream.

The hydraulic and hydrologic characteristics are presented below in Fig. 5 and Table 1. The discharges come directly from a model from the Swedish Meteorological and Hydrological Institute (SMHI) for Sikträskbäcken and Mattjokkbäcken (Vattenwebb - Modelldata per område). For Isbergsbäcken, no data was directly available. The Myer method (Eq. 2) was applied to obtain Isbergsbäcken discharge with the Equation 2 (Piton, s. d.), based on the discharge and the area of the global watershed:

$$Q_{Isb} = Q_w \times \left(\frac{S_{Isb}}{S_w}\right)^\alpha \quad (2)$$

with S_w the reference basin area, S_{Isb} the area of Isbergsbäcken's basin, α a coefficient set to 0.8 according to Piton and Q_w the discharge of the reference's area.

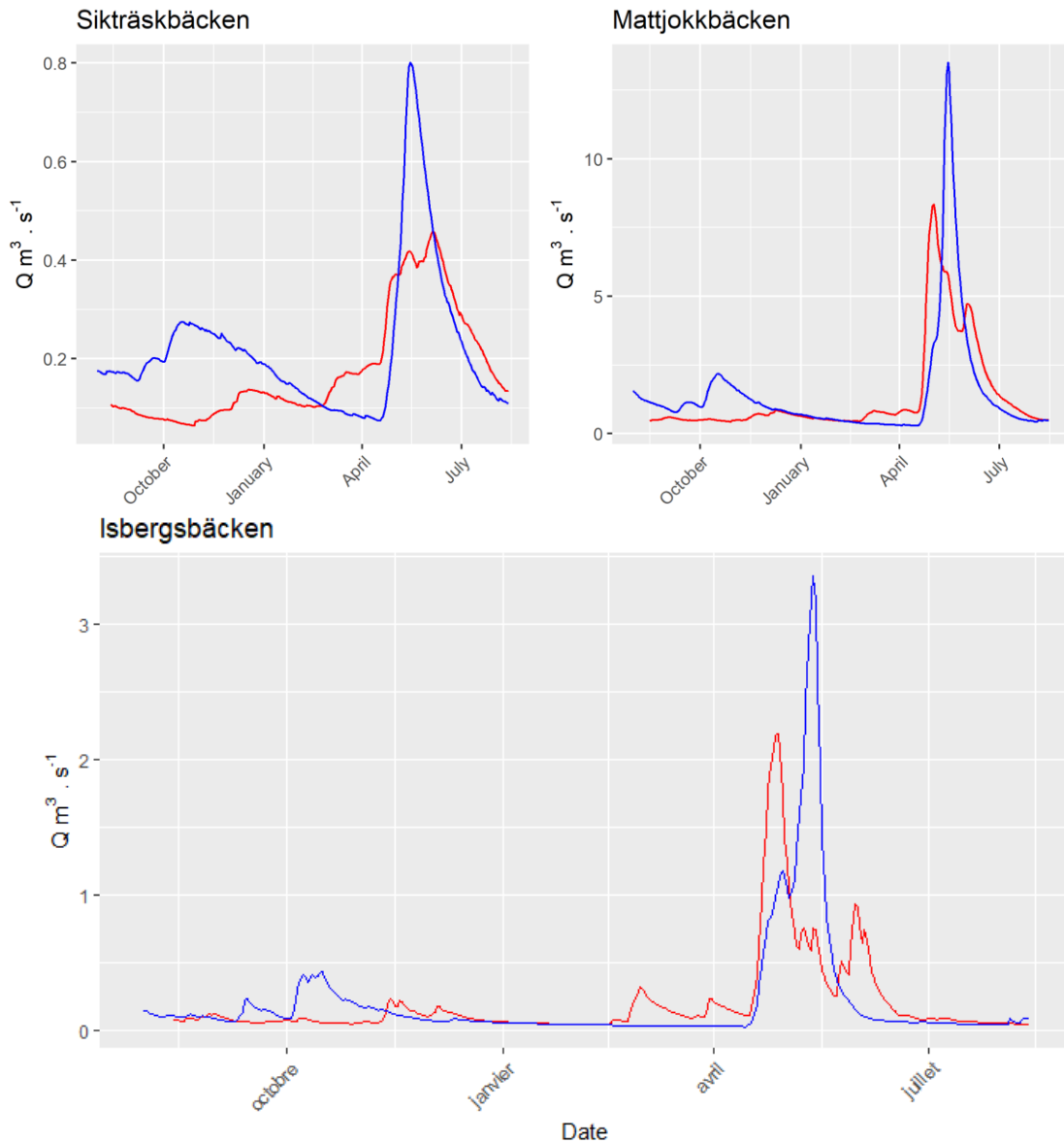


Figure 5: Discharge (m^3/s) in each reach in function of time during the first (blue) and second (red) year of experiment, obtained by modeled data from SMHI

The table below resumes the main rivers' characteristics, the discharge that occurred in the first year are superior to a ten-year return period for Sikträskbäcken and Mattjokkbäcken. The following study must not omit this particular high flow during the first year.

Table 1: Hydrological river characteristics

	Watershed area (km^2)	Mean discharge		Q_{\max} (m^3/s)		Q_{50} (m^3/s)	Q_{10} (m^3/s)
		Year 1	Year 2	Year 1	Year 2		
Sikträskbäcken	18.88	0.22	0.18	0.80	0.46	1.00	0.78
Mattjokkbäcken	126.41	1.48	1.35	13.50	8.34	15.9	12.5
Isbergsbäcken	29.9	0.21	0.20	3.35	2.18		

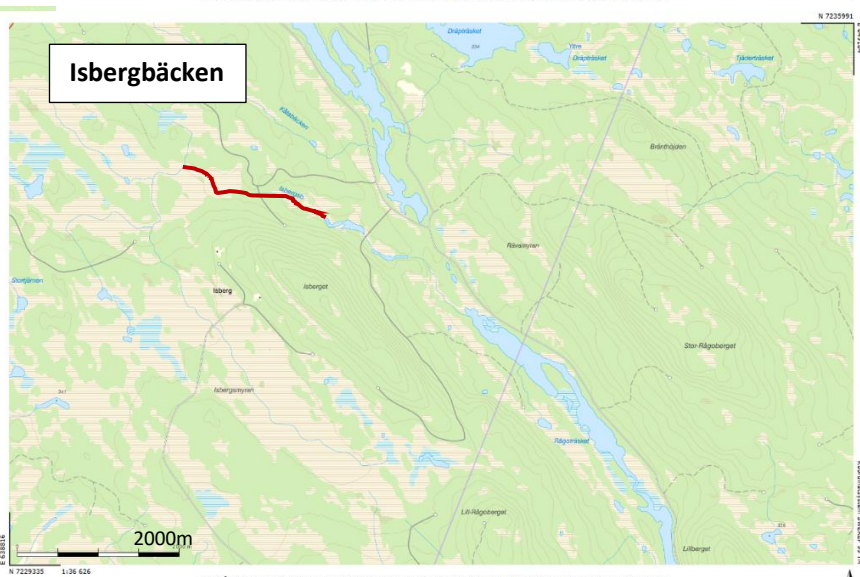
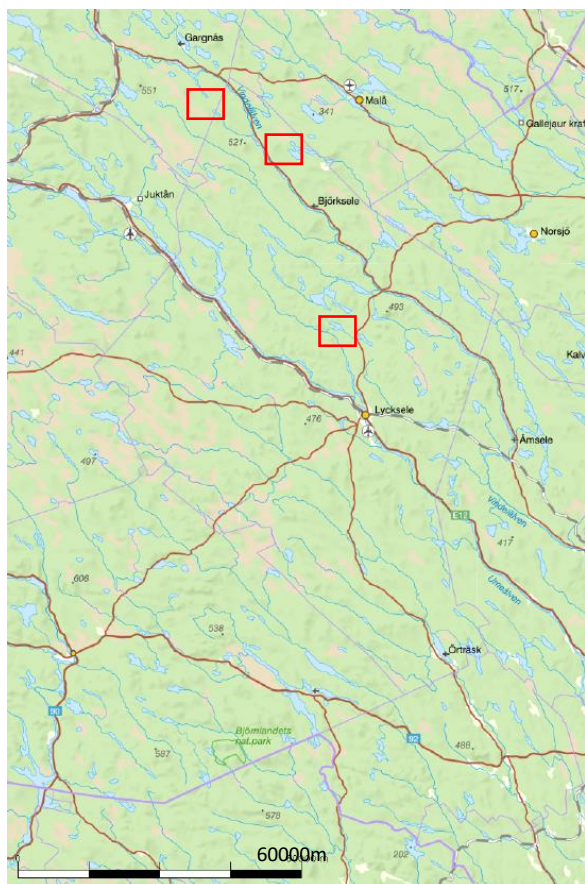


Figure 6: Localization of the study sites; A: localization of the Västerbotten's region ; B: Localization of the three reaches within the Vindelns catchment ; C: Sikträskbäcken ; D: mattjokkbäcken ; E: Isbergsbäcken, from Lantmäteriet

2.2- Field experiment

This study is part of a larger study called MorphoRest surveying several rivers in northern Sweden. The experiment started in August 2017 with the placement of Passive Integrated Transponder (PIT) tracers in the rivers, their positions were then measured successively in August 2018 (Year 1) and August 2019 (Year 2), allowing the occurrence of spring flood by the snowmelt.

2.2.1- PROTOCOL

Each study reach was 100 m long. Each reach was then divided into 10 cross-sections, and for each cross-section, the tracers were equally spaced, implying that in some larger cross-sections, more tracers were introduced.

To measure the coordinates of the tracers, cross-sections topography, boulders' coordinates and protrusion, a total station based upstream emitted a signal to a receptor placed by the searcher at an interesting spot (tracer, boulder or cross-section). The receptor is equipped with a prism that reflects the signal to the station. Based on the time of travel and the speed of the wave emitted, relative coordinates can be obtained. In order to obtain consistent measure from one year to another, the total station must be placed at the same location. Hence, in this experience, three references captors were placed, and made visibly noticeable through flags and painting, to precisely locate the station.

To fully study the processes involved in the river morphodynamic, different morphological parameters were also observed during each field measurement as resumed in the following table:

Table 2: Morphological settings and constraint class

<i>Channel setting</i>	<i>Definition</i>
<i>Morphological settings</i>	
<i>On a step</i>	On a step of a step-pool formation
<i>In a pool</i>	In a pool, area of relative deep water
<i>Riffle/planebed</i>	Area rather open, without major obstacles
<i>In a 'boulder circle'</i>	Arrangement of boulders constraining the tracers
<i>Backwater</i>	Area with a hydraulic perturbation of backwater
<i>Cavity</i>	Local hole in the surface bed
<i>Proximity to boulder class</i>	
<i>Above</i>	The tracer was found upstream of a boulder
<i>Below</i>	The tracer was found downstream of a boulder
<i>Lateral</i>	The tracer was found laterally next to a boulder
<i>On top/under</i>	Tracer on the top of a boulder (2017) or under a boulder (2018,2019)

<i>Constraint class</i>	
Unconstrained	The tracer is not constrained by direct another river material
Shielded	Another bedrock shields the tracer from the upstream flow
Imbricated	The tracer is imbricated between two others clasts
Buried	Need to remove riverbed sediment to visualize the tracer
Embedded	The tracer is firmly fixed in the armor layer

2.2.2- SEDIMENT TRACKING

Originally used to follow up the movement of fish, Radio Frequency and Identification (RFID) and Passive Integrated Transponder (PIT) techniques were adapted to study sediment transport (Camenen et al., 2010.; H. Lamarre et al., 2005; Piégay et al., 2016). The technique consists in the implementation of PIT Tags in preliminary drilled grains recovered by epoxy to ensure the waterproofness of the system.

It allows us to identify each tag with its own code name. The grains were also painted in white and directly identified with their code name written on it. This coloration allows better identification of the fields by direct visualization in the case where the radio frequencies identification would not work. The code name is written directly on the tracer to allows us to identify the tracer if for example, two tracers are very closed. (H. Lamarre et al., 2005) Passive transponders have been proved as reliable, cheap, and long-lasting devices to study sediment transport, especially for long term studies like this one. Recovery rates of the tracers are presented in the following table:

Table 3: Recovery rate of tracers

	Number of tracers introduced	Recovery rate	
		<i>Year 1</i>	<i>Year2</i>
Sikträskbäcken	190	88.4%	86.8%
Mattjokkbäcken	254	81.7%	80%
Isbergsbäcken	352	83.6%	88.6%

The recovery rate of tracers using the PIT Tags method is always higher than 80%. The recovery rates are satisfying and are in the same order of magnitude as observed by Vázquez (Vázquez-Tarrío et al., 2019), thus it can be considered as totally significant to collect enough data. The lower rate in Mattjokkbäcken can be explained by the fact that transport distances were higher in this river, making it more difficult to find back tracers, compared to Isbergsbäcken for example where tracers moved closer to their former position facilitating the research.

2.3- Analysis method

2.3.1- DATA PREPARATION

The first step of the study was to properly organize data. For each year of experiment, recovered tracers were filtered and the transport distance was calculated with the Pythagorean theorem based on the North and East coordinates. Bankfull depth was obtained along cross sections by the difference of average depths of right and left bankfull and the point's depth. Boulder's diameters (D_{boulder}) were calculated between upstream and downstream coordinates. Boulders' protrusion was determined with an average of the difference between top and upstream z-coordinates and the top and downstream z-coordinates.

In order to visualize the transport and the river settings, a map of each reach was created with ArcGIS with the planform, the bankfull depths, the boulders represented with a buffer with the diameter D_{boulder} obtained before. Transport vectors were obtained with the point to line function on ArcGIS based on a data pretreatment to apply the function and considering the movement as a straight line from the first year's position to the second one (Hélène Lamarre & Roy, 2008). Besides having a global view of the experiment, ArcGIS permitted to calculate the distance between tracers and boulders using the "near tool" and to have a global idea of the river depth where tracers are, joining the depth table to the tracers table choosing the closest depth. Furthermore, it allowed having a global view of the results to stress key points to explore and identify outliers' points from mistakes made on the field when identifying the tracer's names.

2.3.2- RIVER GRAINS AND TRACER'S CHARACTERIZATION

From the sedimentary study carried out in the rivers, it is possible to draw the granulometric curve characterizing the bed of the three reaches. It is common to distinguish 3 characteristic effective particle diameters D_x where X represents the percentage of grains less than or equal to diameter D. Thus, we obtain the D_{84} , D_{50} and D_{16} presented in the table below:

Table 4: Riverbed characteristic grain sizes for the three reaches including $D > 256\text{mm}$

	Sikträskbäcken	Mattjokkbäcken	Isbergsbäcken
D_{16} (mm)	20	100	274
D_{50} (mm)	270	266	432
D_{84} (mm)	868	751	894
Uniformity coefficient (Cu)	36	5.3	4.3

To characterize quickly the river beds, the uniformity coefficient was calculated with the formula below and given in the table 4:

$$Cu = \frac{D_{60}}{D_{10}} \quad (3)$$

From this simple characterization, Sikträskbäcken appears to be the more graded with a spread grain size distribution with a higher rate of small particles than Mattjokkbäcken and Isbergsbäcken that seem to have more homogeneity in their grain distribution.

With the bed analysis, it is possible to establish the grain size distribution in the reaches and to compare it with the distribution of tracers introduced in the respective reaches (Fig. 7). Globally, the tracers' size is smaller than the riverbed grain size, this can be explained because the riverbed grain analysis takes into account the large boulder with a size higher than 1m. This increases the D_{84} and shifts the curves to the right. Also, the maximal B-axis for tracers is 256mm. Since bigger bed material can only be transported during exceptional high flow, it is more representative to exclude clasts higher than 256mm to study the transport for flow more susceptible to occur during the experiment (Hélène Lamarre & Roy, 2008).

Thus, tracer distribution matches the sediment grain size distribution for $clast < 256mm$.

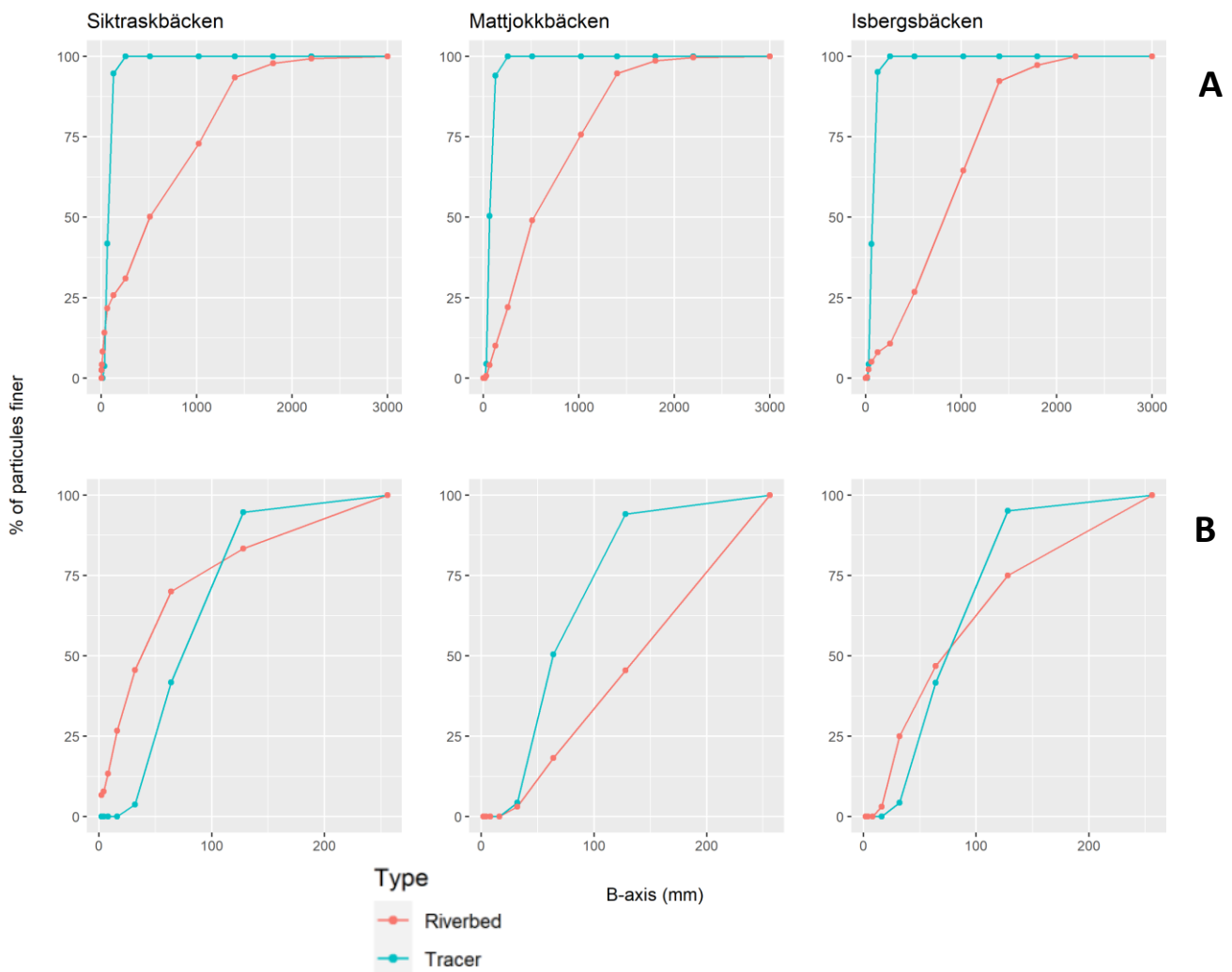


Figure 7: Distribution of sediment size of the riverbed and tracers' sizes based on the intermediate axis, (A) Including the sediments with intermediate axis higher than 256mm, (B) Excluding the sediments with intermediate axis higher than 256mm

Table 5: Riverbed characteristic grain sizes for the three reaches excluding $D > 256\text{mm}$

	Sikträskbäcken	Mattjokkbäcken	Isbergsbäcken
D_{16} (mm)	5	59	25
D_{50} (mm)	18	138	66
D_{84} (mm)	69	219	175

Even if the D_{84} of each reach is similar, the density of boulders is not the same in each river. Indeed, Isbergsbäcken is the most “bouldery” river with a boulder density of 20.6% followed by Sikträskbäcken with 19.2% and finally, Mattjokkbäcken has less boulder surface with 13.6%. It has to be noted that this density was calculated based on the surface of each boulder buffer so the reality can be different depending on the shape of the boulders.

- **River slopes:**

The riverbed slope is a major characteristic of sediment transport, as it can directly be correlated with the critical Shields coefficient (Lamb et al., 2008). The measurement of coordinates can be used to calculate the mean slope of the rivers based on river banks coordinates. Longitudinal profiles are presented in Fig. 8. If Mattjokkbäcken seems to have a quiet constant slope along the reach, Sikträskbäcken and Isbergsbäcken have different local slopes which can create different local Shields stress. Even if the calculation is questionable because it lacks some measurements upstream and downstream the reach to have a fully comprehensive appreciation of the slopes, it still gives us an order of magnitude of the difference of the slopes along the reaches.

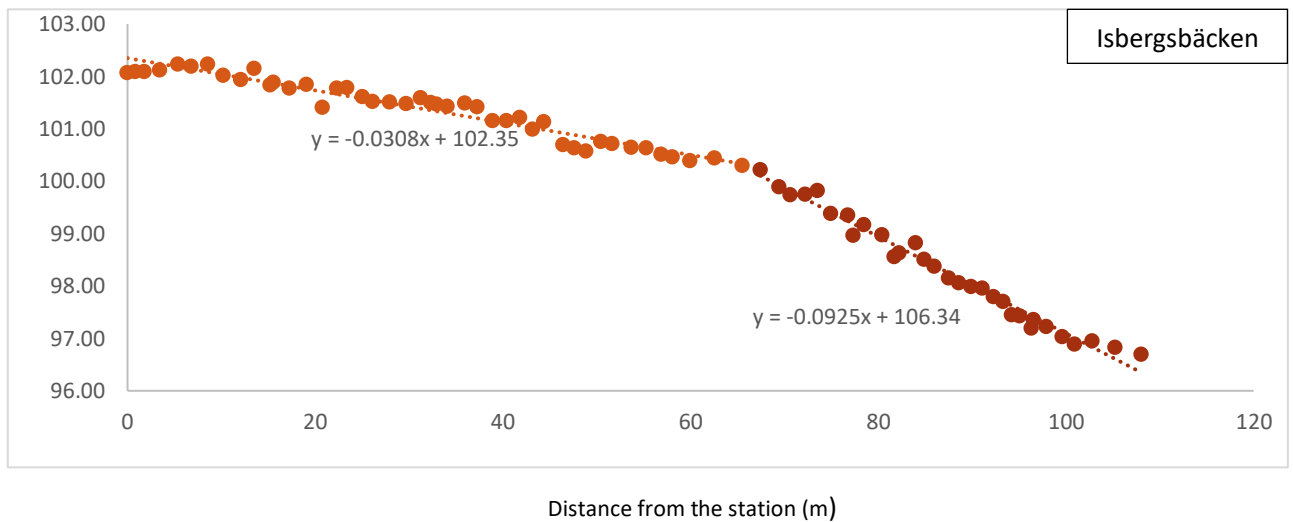
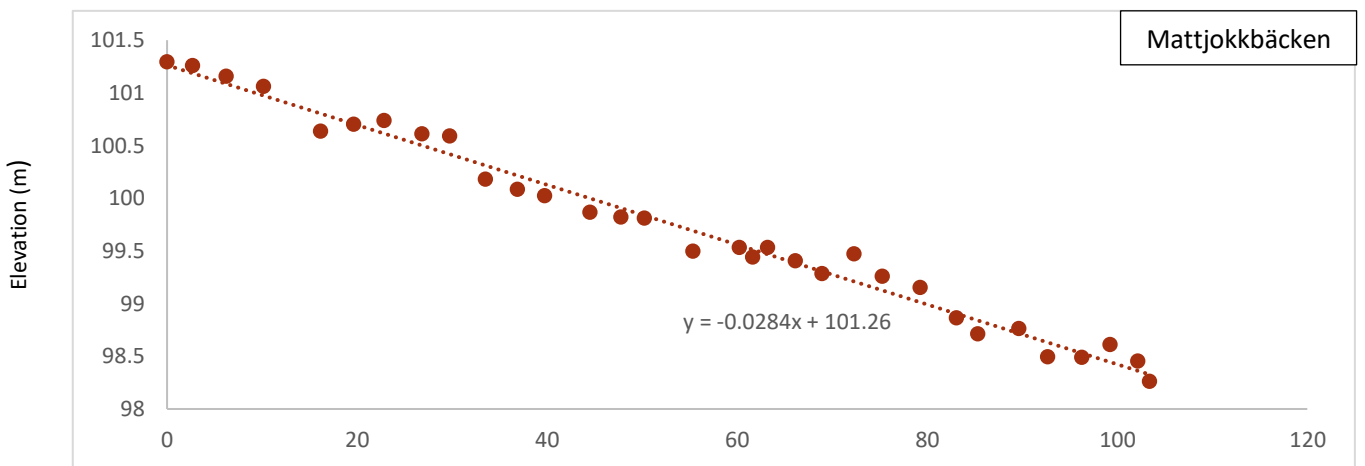
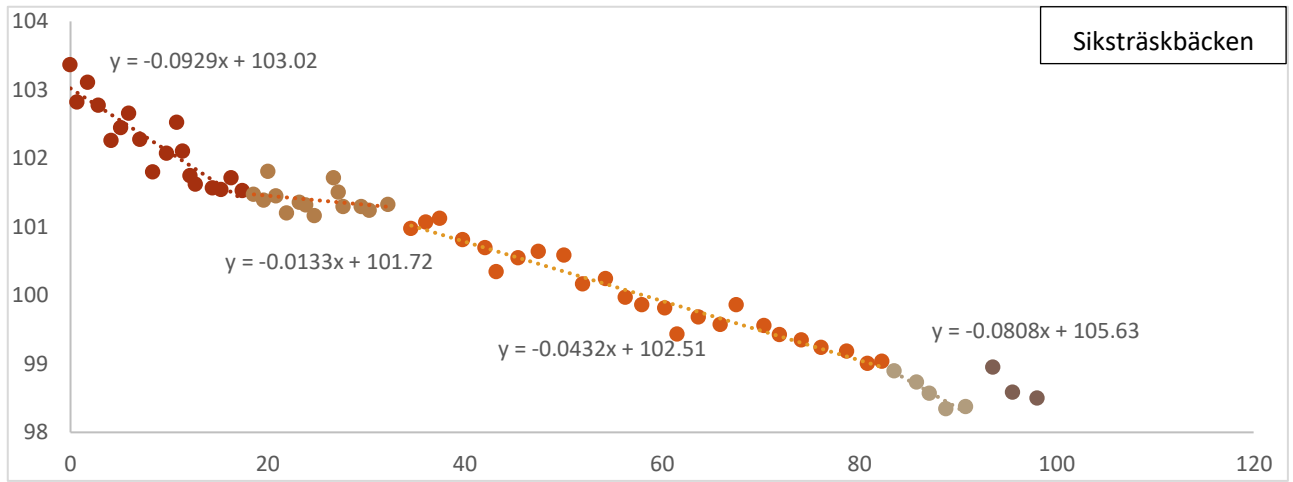


Figure 8: Graph representing the local slopes of Sikträskbäcken, Mattjokkbäcken and Isbergsbäcken; slope is given by the coefficient of each linear trendline

2.3.3- CALCULATION OF SHEAR STRESS

As described previously shear stress is a major parameter to consider when studying sediment transport (Charlton, 2007) especially in this study aiming to observe the impact of boulders in the stream. It is obtained with the equation (Eq. 4) :

$$\tau = \rho g S h \quad (4)$$

where τ is in N/m^2 , h is the depth (m) and S is the local bed slope, and g the acceleration due to gravity (9.81 m s^{-2}). In this study, the shear stress will exclusively designated shear stress at bankfull conditions determined with h = depth at bankfull conditions. In terms of discharge, it is often assumed that bankfull flow is a representative discharge in the same order of magnitude as flood around 2 years of return period (Church et al., 2012).

From this shear stress, it is possible to calculate the dimensionless shear stress also called Shields parameter (Eq. 5):

$$\tau^* = \frac{\tau}{\rho_s - \rho_w} \times g \times D \quad (5)$$

Where, τ = shear stress in N/m^2 , ρ_s =density of sediment (kg/m^3), ρ_w =density of water (kg/m^3), g =acceleration of gravity (9.81 m/s^2), D = size of the grain (m).

Historically, sediment transport aims to determine if sediments are likely to move as a function of physical parameters of the river. To determine if the particle is susceptible to move or not, the notion of critical Shields stress (τ_c^*) was introduced. It characterized the threshold after which there is a transport. Shields showed that the critical Shields stress tends to converge towards 0.06, which is the commonly used value of τ_c^* . Different authors suggested other values for τ_c^* for instance (Meyer-Peter & Müller, 1948) set τ_c^* equal to 0.047, and Parker (2003) suggested $\tau_c^*=0.03$ twice less than Shields' value. (Parker et al., 2003) But, as exposed previously, a fixed value of τ_c^* would omit important interaction in the riverbed. Hence, it is important to set the τ_c^* to a value matching our stream's characteristics. Lamb studied the relationship between the river slope and the critical Shields stress, fitting flume and field data, they found this relationship (Eq. 6) below (Lamb et al., 2008):

$$\tau^*_{c} = 0.15 \times S^{0.25} \quad (6)$$

Where, S is the slope and 0.25 and 0.15 coefficients obtained by regression.

To easily visualize if Shields parameter is superior to critical Shields stress, the following critical ratio (Eq. 7) was applied:

$$critical \ ratio = \frac{\tau^*}{\tau^*_{c}} \quad (7)$$

A critical ratio below 1 means that no transport is predicted and if the ratio is superior to 1, the prediction supposed that a movement should be observed.

2.3.4- ANALYSIS OF SIGNIFICANT DIFFERENCES BETWEEN CLASTS (ANOVA TEST)

To study the influence of the different classes reported on the field (constraint class, global morphological class, ...), an analysis of variance was performed. This analysis, also called one-way analysis of variance (ANOVA), aims to compare the means of the different classes e.g. constraint, morphology, etc., in order to determine if there is a significant difference between at least two classes.

ANOVA test hypotheses:

H₀: The means of all groups are the same

H₁: At least one mean is different from the others

Assumptions required for ANOVA test:

- Independence of the observations verified with the Durbin Watson test on R,
- The data of each factor level are normally distributed, verified with the Shapiro test on R,
- These normal populations have a common variance. (Barlett's test can be used to check this.)

Given the empirical aspect of this study, data are not well normally distributed. To correct this in order to perform an ANOVA, data were transformed following a Tukey transformation, thus a lambda coefficient is found to best fit a normal distribution. The result before and after transformation can be found in the Appendix 7.5.

According to the p-value obtained, it is possible to know if at least one group has a different mean. In order to identify this group, a post hoc test can be performed. Here a Tukey Honest Significant Differences (HSD) was computed as a multiple pairwise-comparison between the means of groups.

2.3.5- SPEARMAN CORRELATION MATRIX

Considering the empirical aspect of this study, it seems unlikely that the distribution of the different influencing parameters (grain size, slope, distance to boulder,...) would clearly follow a linear correlation. This is why it was chosen to study the monotonic correlation between the variables. The Spearman correlation studies the monotony between two variables by assigning a coefficient between [-1 ;1] called Spearman's coefficient. There is no threshold value to assert the correlation between two variables, but the closer the absolute value of the coefficient is to 1, the stronger the correlation. Each coefficient is associated with a p-value reflecting the significance of the result obtained.

3- RESULTS

3.1- Overview of tracers' mobility

As a first sight on the tracers' mobility, the mobile fraction (F_m) was determined through the equation 8. It should be reminded that only tracers with transport distance greater than 0.05m were considered mobile, to take into account the uncertainty due to the use of the total station to measure the coordinates. The results presented in table 6, first show that the F_m is higher for all reaches the first year than the second. This can be explained by the fact that in the spring of 2018, flows in the river were higher than in 2019 in all three rivers. It should also be noted that when the experiment was set up, the tracers were placed so that they were equidistant along the cross-section. Thus, several tracers were introduced in places that could be characterized as "unstable", such as on a rock. Whereas after one year of the experiment, the flow naturally put them at equilibrium, which made them less mobile the following year.

Secondly, we can see high mobility the first year for Mattjokkbäcken with 93% of mobile tracers, around 30% more than the two other reaches for the same year, and 30% more than the second year in Mattjokkbäcken, probably linked to the high discharge that occurred in 2017 in Mattjokkbäcken. The very low mobility observed in Isbergsbäcken the second year, with only 28% of mobile tracers can be explained by the high number of boulders in the stream with a boulder's density 7% higher than in Mattjokkbäcken. There is no reference discharge for Isbergsbäcken but if we compare the discharges from the year 1 around $3\text{m}^3/\text{s}$ and the second year around $2\text{m}^3/\text{s}$, so $1\text{m}^3/\text{s}$ less, and yet more than 30% of F_m less the second year, it can be assumed that due to the equilibrium found the second year is mostly responsible of the lower mobility and not the discharge.

$$F_m = \frac{\text{Number of mobile tracers } (L > 0.05\text{m})}{\text{Total number of tracers recovered}} \quad (8)$$

Table 6: Fraction of mobile tracers after each year of experiment in the three reaches

	Fraction of mobile tracers (F_m)	
	Year 1	Year 2
Sikträskbäcken	66.9%	53.8%
Mattjokkbäcken	93.7%	60.9%
Isbergsbäcken	59.2%	27.9%

3.2- Grain size and transport distance

The representation of the mean centered transport distance of the tracers as a function of their B-axis size (graph 9) firstly confirms that the transport is more important after the first year of experiment than after the second year. Not only in terms of frequency but also of transport distance, especially for Mattjokkbäcken with a transport distance 7 times greater the first year up to 40m.

Table 8 highlights the major transport distance and shows the B-axis associated to the maximal travel distance. First, we can notice that the $D_{L_{max}}$ is higher the second year for Sikträskbäcken and Mattjokkbäcken and smaller for Isbergsbäcken. Comparing the $D_{L_{max}}$ diameter to characteristic diameters of the riverbed, we can see that for the three reaches $D_{L_{max}}$ is inferior to the D_{16} . Which would mean that the finer fraction of the bed is the more able to have greater transport distance.

Table 7: General transport characteristics for all reaches and for both year of experiment, D always refers to the B-axis of the grain, L stands for the transport distance (respectively minimal, maximal, median and mean distance, τ_c^* stands for the critical Shields stress

		D_{16}	D_{50}	D_{84}	$D_{L_{MAX}}$	L_{MIN}	L_{MAX}	L_{MED}	L_{MEAN}	τ_c^*
SIKTRÄSKBÄCKEN	Year 1	20	270	868	34	0.052	1.953	0.177	0.27	0.261
	Year 2				73	0.051	0.864	0.104	0.18	0.472
MATTJOKKBÄCKEN	Year 1	100	266	751	62	0.057	44.363	0.819	4.34	0.159
	Year 2				89	0.050	6.565	0.171	0.53	0.151
ISBERGBÄCKEN	Year 1	274	432	894	91	0.051	1.283	0.165	0.23	0.208
	Year 2				54	0.050	0.522	0.093	0.16	0.273

The graphs (Fig.9) do not show a linear correlation between transport distance and grains size following the B-axis, instead there is sort of a threshold where grains with a B-axis greater than 100mm appear less mobile. This threshold can be nuanced because as we can see few tracers have B-axis higher than 100mm. But what can be noticed from this analysis is that the correlation between grain size and transport distance is not as clear as it would be expected.

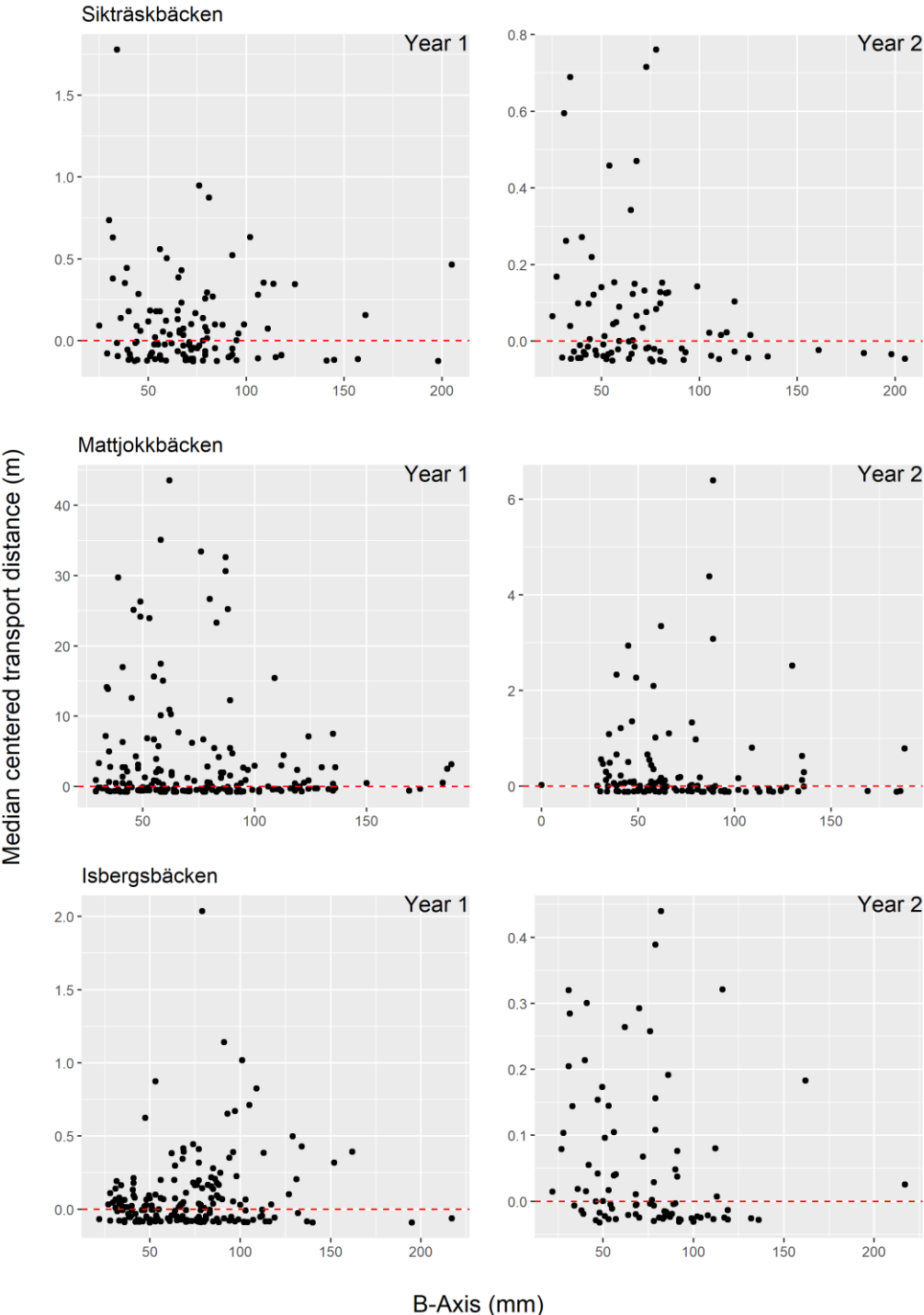


Figure 9: Median centered transport distance in function of grain size following the B-axis, excluding the immobile tracers ($L < 0.05$)

The hypothesis that maybe the B-axis is not the most representative one was then emitted. In order to quantify the correlation between the different axis and the movement, the Spearman coefficient was determined. Only the results in green should be considered as it shows the significant values at a level a significance of 0.05. Even if with this method of correlation, there is no threshold value to consider a correlation between two parameters, here the correlations are very low. It can be assumed that less than 0.1 of correlation is not significant. So even if, the A-axis seems more significative for Mattjokkbäcken, it will not be taken into account for the following analysis. It can still be noted the correlation are always negative, in favor of a greater transport for smaller grains.

Table 8: Spearman coefficients to determine correlation between travel distance of grains and their grain size attributes, in green the significant values, with p-value set to 0.05

		A-axis	B- axis	C- axis
Sikträskbäcken	YEAR 1	-0.10	-0.087	-0.12
	YEAR 2	-0.074	-0.061	-0.044
Mattjokkbäcken	YEAR 1	-0.07	-0.06	-0.044
	YEAR 2	-0.18	-0.20	-0.18
Isbergsbäcken	YEAR 1	-0.04	-0.04	-0.07
	YEAR 2	-0.14	-0.16	-0.16

To determine whether there is an Equal Mobility Transport, the Fig. 10 shows the transport distance scaled by the mean transport distance in relation to tracer's B-axis scaled by the bed surface D_{50} and their linear regression (tracers that did not move were excluded). A b near 0 would be in favor of an EMT theory and a negative b would attest an SST theory. To assess the significance of the regression slope, a statistical test is lead on the slope coefficient, with $H_0: b=0$ at the level of significance $\alpha= 0.05$. (Hélène Lamarre & Roy, 2008) Here, no graph shows a significant p-value except the first year in Isbergsbäcken, so even though in the other rivers, the slope is negative, the results don't have a statistical significance sufficient to conclude on the transport type. The only significant result has a positive slope which corresponds to neither theory.

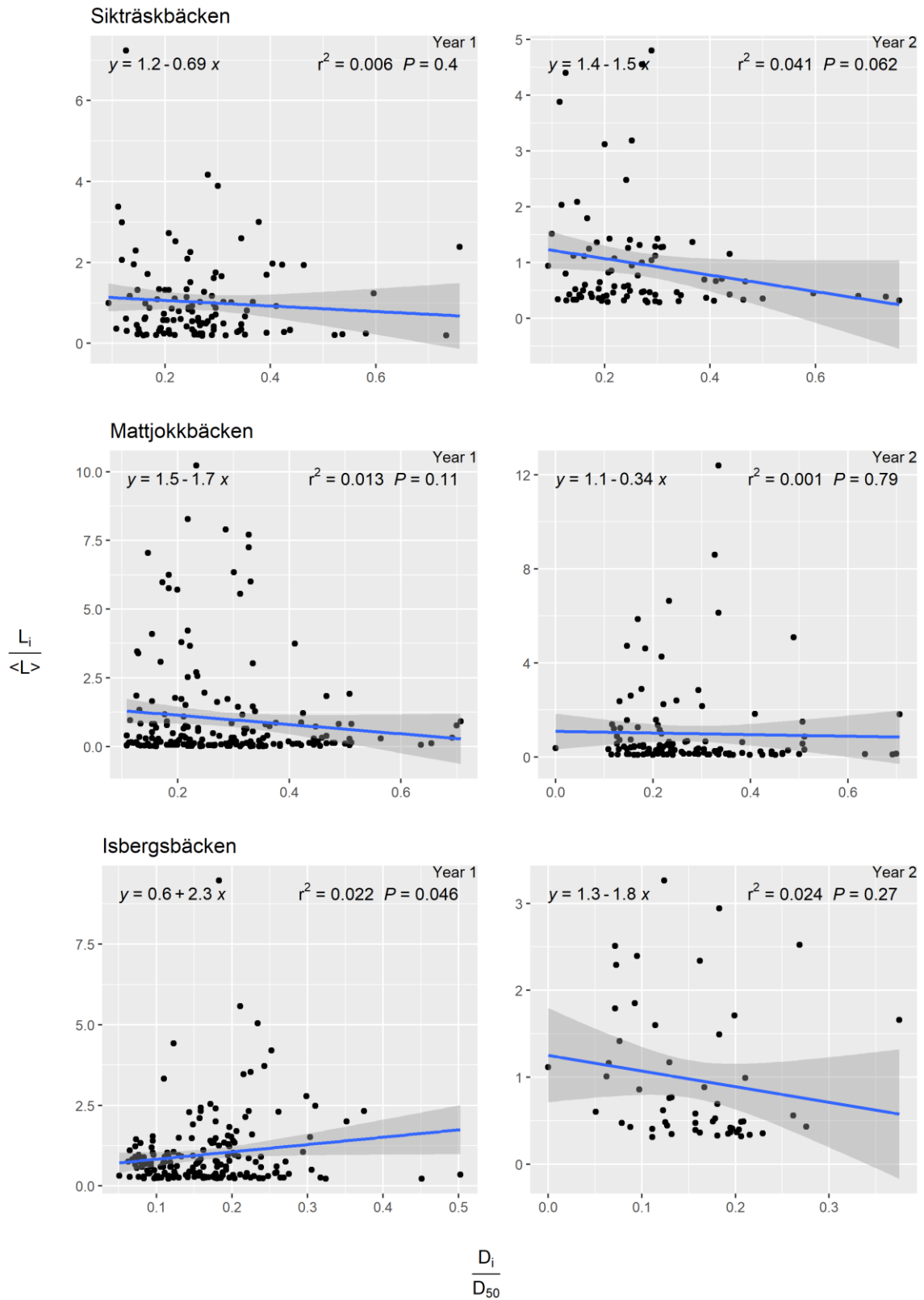


Figure 10: Transport distance scaled by mean transport distance in relation with tracer B-axis scaled by the bed surface D_{50} (including the sediment >256mm) and linear regression (tracers that did not move were excluded).

3.3- Influence of constraintment class

As presented before, a constraintment class was given each year of experiment to each tracer to characterize if the tracer was either buried, shielded, imbricated, embedded or unconstrained. The first year, considering that the tracers were introduced in the stream, their constraintment classes are not complex, mainly shielded and unconstrained. Also, the proportion of each constraintment class introduced is quite similar in the three rivers, to have a certain homogeneity between the three reaches. Table 9 shows that the tracers tend to become more constrained after several floods, the number of unconstrained tracers decreases in favor of more complex positions in the river. It should be noted that the sum presented in this table can differ from the number of tracers recovered because some tracers considered to have been recovered could not be exploited because they were subject to surveying errors in the field.

Table 9: Number of tracers in each constraintment class during the three years of study and for the three reaches

	Sikträskbäcken			Mattjokkbäcken			Isbergsbäcken		
	2017	2018	2019	2017	2018	2019	2017	2018	2019
Unconstrained	106	54	48	90	43	43	176	107	39
Shielded	62	69	56	78	56	54	138	181	83
Buried	0	24	21	1	55	53	0	10	4
Embedded	0	10	25	9	33	44	0	11	30
Imbricated	0	0	0	0	8	4	0	2	2

After running an ANOVA, a significant difference between unconstrained and shielded classes appears for Sikträskbäcken and Isbergsbäcken showing a significant greater transport for unconstrained tracers (Fig. 11). We could have expected similar results for the following year, but the results are more mixed. Indeed, the unconstrained class does not have greater transport distance, it even shows a significant greater transport for the buried class for the three reaches. Knowing that the first year of experiment, tracers were placed in unstable location, results from the second year are more relevant, showing the natural sediment process. Finally, the constraintment class seems to have only a limited impact on sediment transport, with more mobile tracers in unconstrained class when sediment is not at equilibrium but after reaching this stability, a more complex relationship seems to appear where constrained class (buried) moved further than unconstrained class.

3.4- Role of river morphology

The assessment of river morphology control over sediment transport did not reveal significant results after an ANOVA test. Moreover, the step and pool formations were very few represented, which does not allow us to have consistent statistic on it. This morphologic setting can be interesting to follow through time if maybe more data are collected in the future.

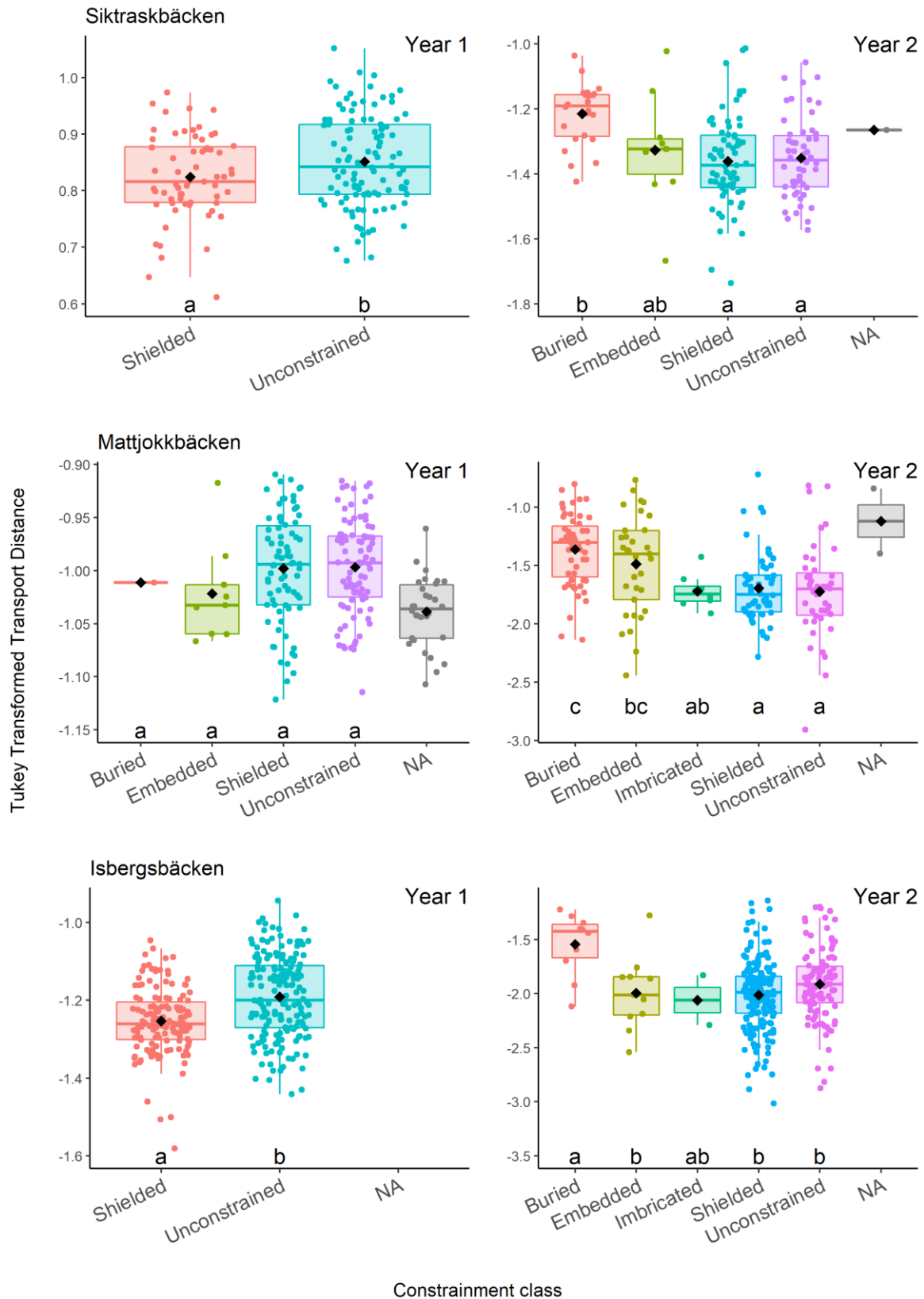


Figure 11: Box plot comparing tracer transport distance by constraint class. Letters below each plot shows significant pairwise differences in means ($P < 0.05$) (Tukey's HSD following ANOVA on Tukey transformed data). The box plots indicate upper and lower quartiles as box ends, 10th and 90th percentiles as whiskers, and median values as the line within each box.

3.5- Influence of the proximity to boulders

Relying on studies on the influence of boulders on the river’s hydraulic, it was important to analyze the transport distance in function of the tracer’s distance to a boulder. To highlight the relative position to the boulders a colorization was applied to visualize the different types of proximity (Fig. 12). No clear cluster can be observed, showing a great variability associated to their repartition. But as explained in part 1.4.1, the hydraulic impact of a boulder on the flow differs upstream and downstream but also laterally. From this, it is interesting to distinguish between the different position of the tracers relatively to the boulder: upstream, downstream or next to the boulder. Sometimes a more complex arrangement was observed where the tracer could be at the same time lateral to a boulder and directly upstream or downstream. An ANOVA test (Fig. 13) was conducted, revealing a significant difference only between lateral and upstream/downstream position for Sikträskbäcken during the second year. Globally, the configuration both upstream and downstream boulders has the lowest transport distance even if no significant difference has been found. It can be noted that this study takes into account tracers placed up to 5m from a block. At this distance the influence of a boulder can be negligible. This is why an ANOVA test was also carried out to study the influence of a boulder located at less than 1 meter from a tracer (1) (the tracers further than 1m are represented by 0). Here the information on the relative position of the tracers in relation to the boulder is lost. The results show that no significant differences are found except for the first year of the study in Isbergsbäcken, which is also matching the result of the Spearman correlation test with a significant negative correlation to the transport distance (Table 10). A greater number of tracers would have made possible the combined study of relative position within 1m closed to boulder.

From those analyses, no clear strong correlation appears when speaking of proximity with boulders but it rather seems to create a highly variable transport. It also shows the great variability of results in the field. The study of the accuracy of incipient prediction through the critical ratio can be interesting, to see if the transport in those rivers can be predicted with “classic” equations or if boulders really control the transport, even if it is in a more variable way as observed in this paragraph.

Table 10: Spearman coefficients to determine correlation between travel distance of grains and their grain size attributes, in green the significant values, with p-value set to 0.05

		Distance to boulder
Sikträskbäcken	YEAR 1	-0.09
	YEAR 2	-0.15
Mattjokkbäcken	YEAR 1	-0.06
	YEAR 2	-0.1
Isbergsbäcken	YEAR 1	-0.24
	YEAR 2	0.04

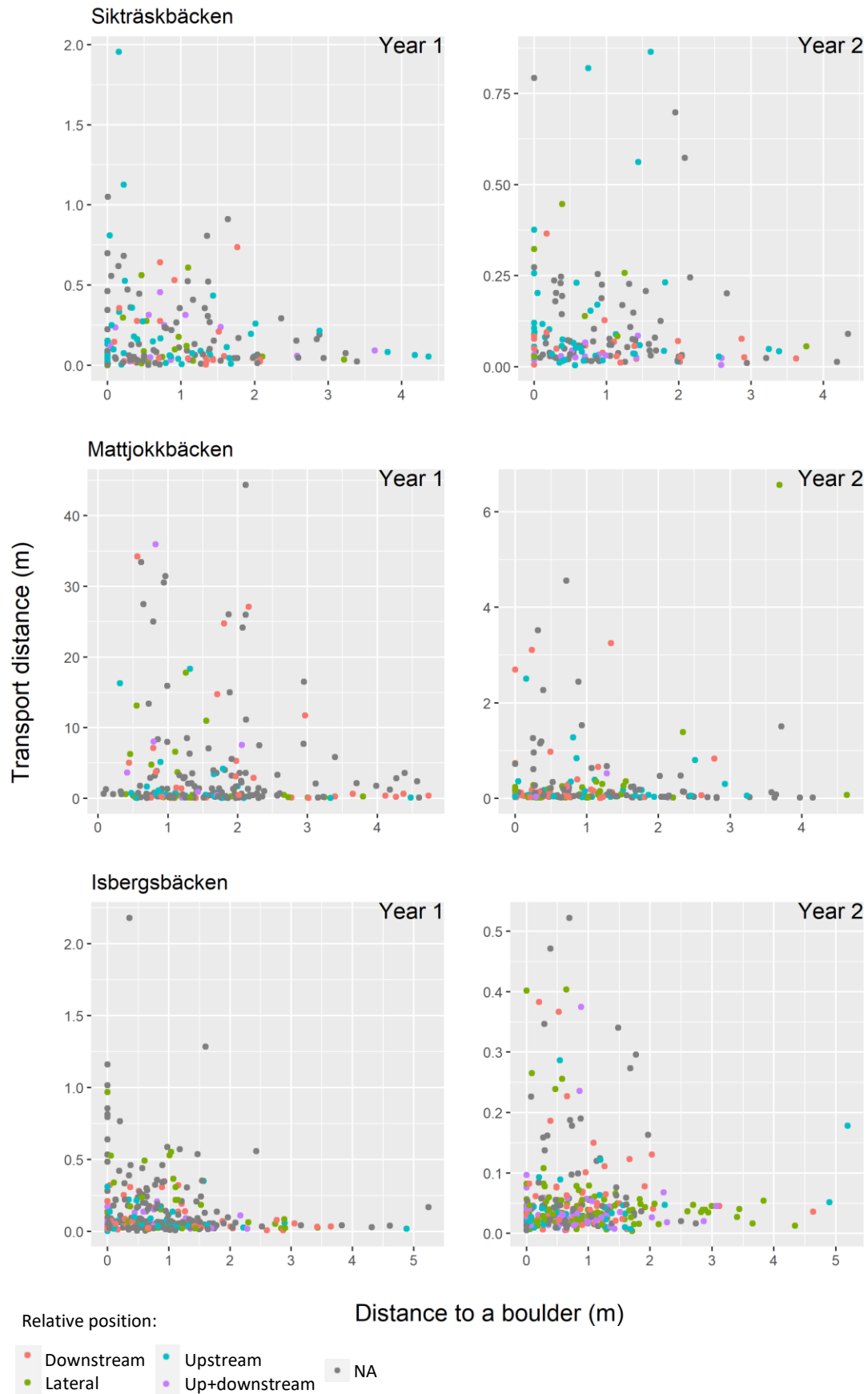


Figure 12: Transport distance (m) in function of the tracers' distance to the closest boulder (m), the colorization represents the relative position to the closest boulder

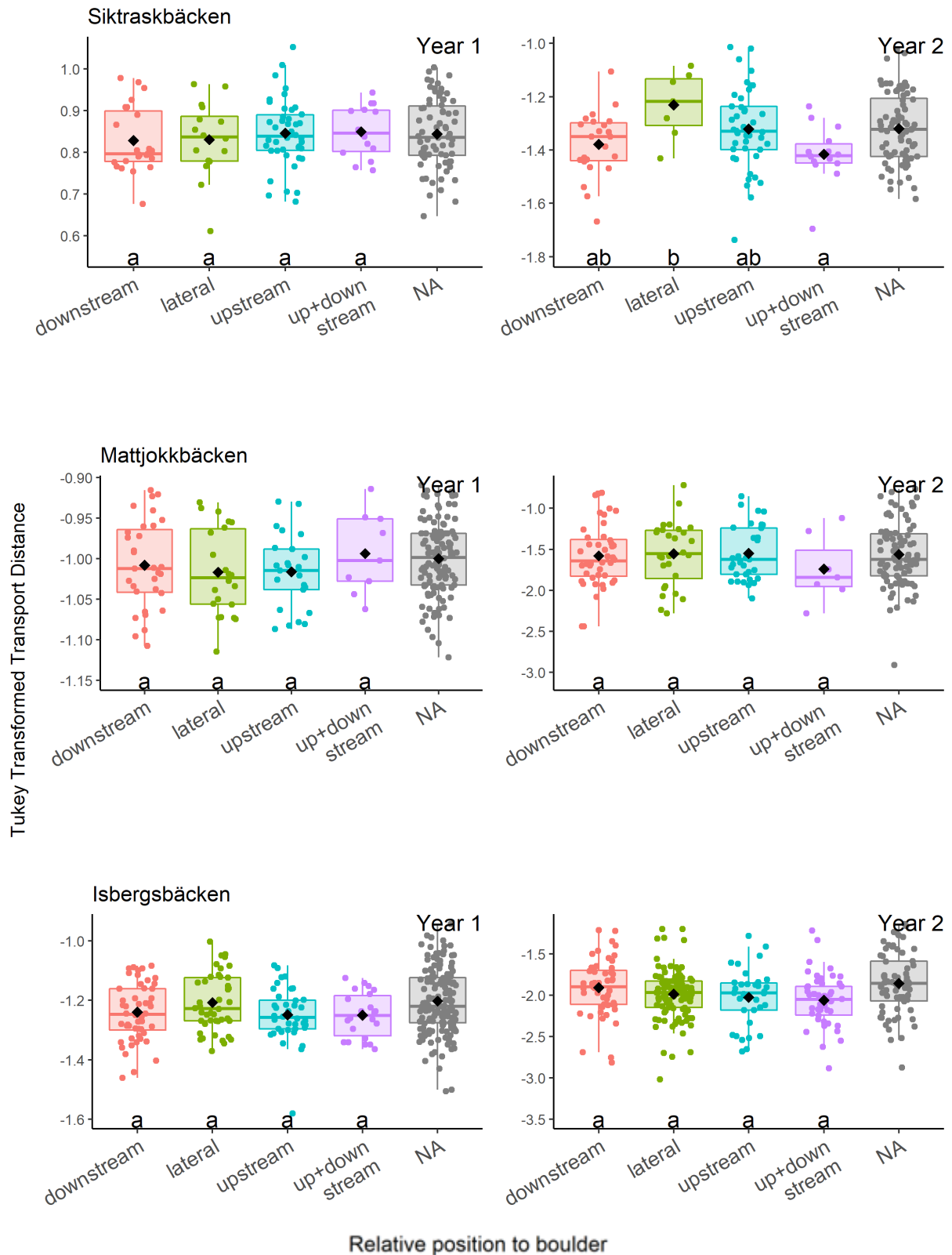


Figure 13 : Box plot of the tracer transport distance in function of their relative position to a boulder, 1 for a tracer closer than 1m to a boulder and 0 for a tracer further than 1m. Letters below each plot shows significant pairwise differences in means ($P < 0.05$) (Tukey's HSD following ANOVA on Tukey transformed data). The box plots indicate upper and lower quartiles as box ends, 10th and 90th percentiles as whiskers, and median values as the line within each box.

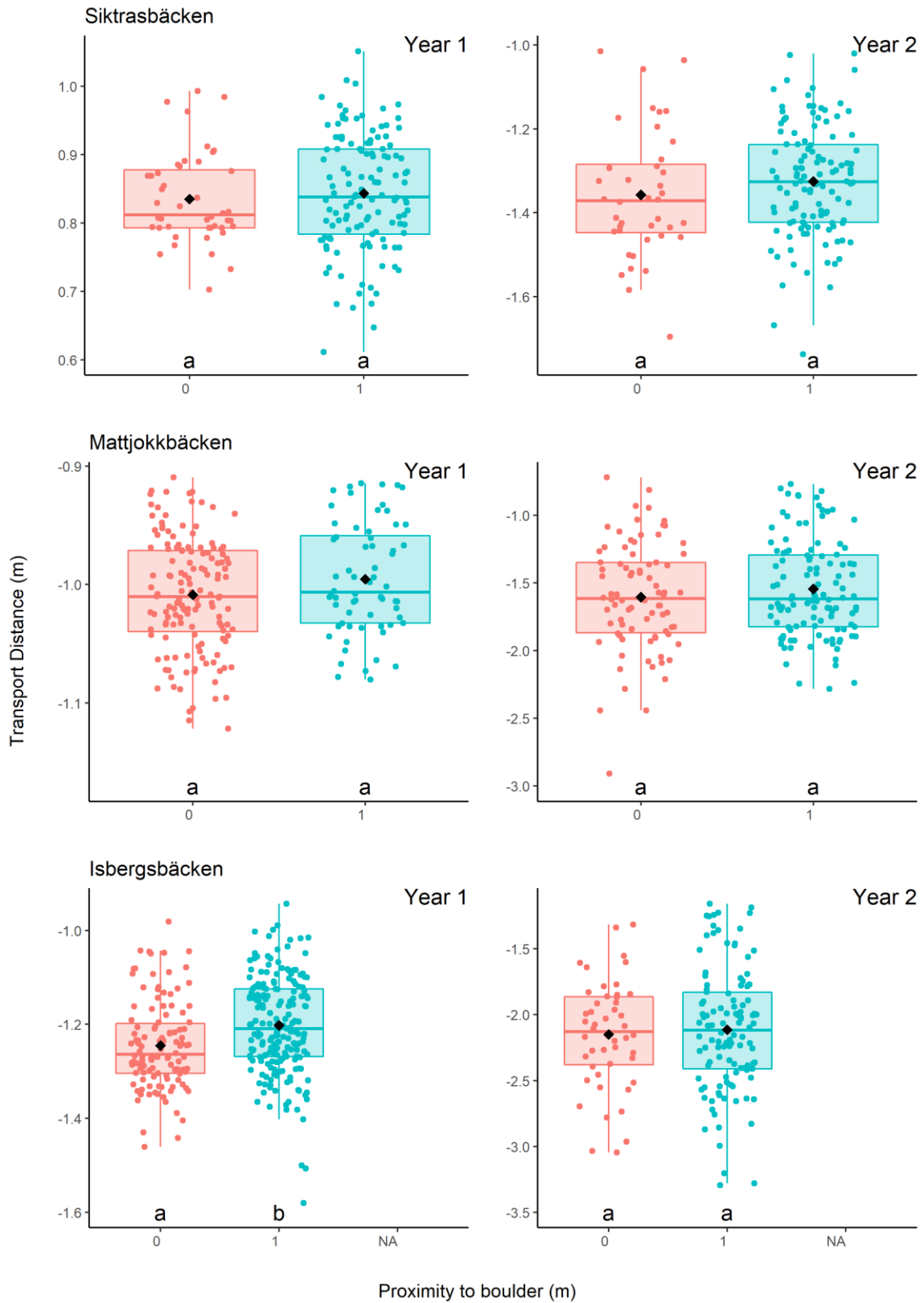


Figure 134: Box plot of the tracer transport distance in function of their proximity to a boulder, 1 for a tracer closer than 1m to a boulder and 0 for a tracer further than 1m. Letters below each plot shows significant pairwise differences in means ($P < 0.05$) (Tukey's HSD following ANOVA on Tukey transformed data). The box plots indicate upper and lower quartiles as box ends, 10th and 90th percentiles as whiskers, and median values as the line within each box.

3.6- Influence of the slope

As mentioned in the paragraph 1.4.1 the role of the slope in sediment transport has been largely studied. Here the aim is to determine the influence of slope in a protruding stream. The analysis will focus on the differences of transport between local slopes within the same reach.

ANOVA tests were performed relatively to the different local slopes within the same reach. Mattjokkbäcken was not represented because for this reach only one slope was considered as there was no major difference in its bed topography. Fig. 15 shows a significant greater transport distance for greater slopes in both Sikträskbäcken and Isbergsbäcken. This shows that the slope has an important influence on the sediment control, but contradicts what Lamb asserts, where a steeper slope would require more shear stress and thus be less conducive to movement.

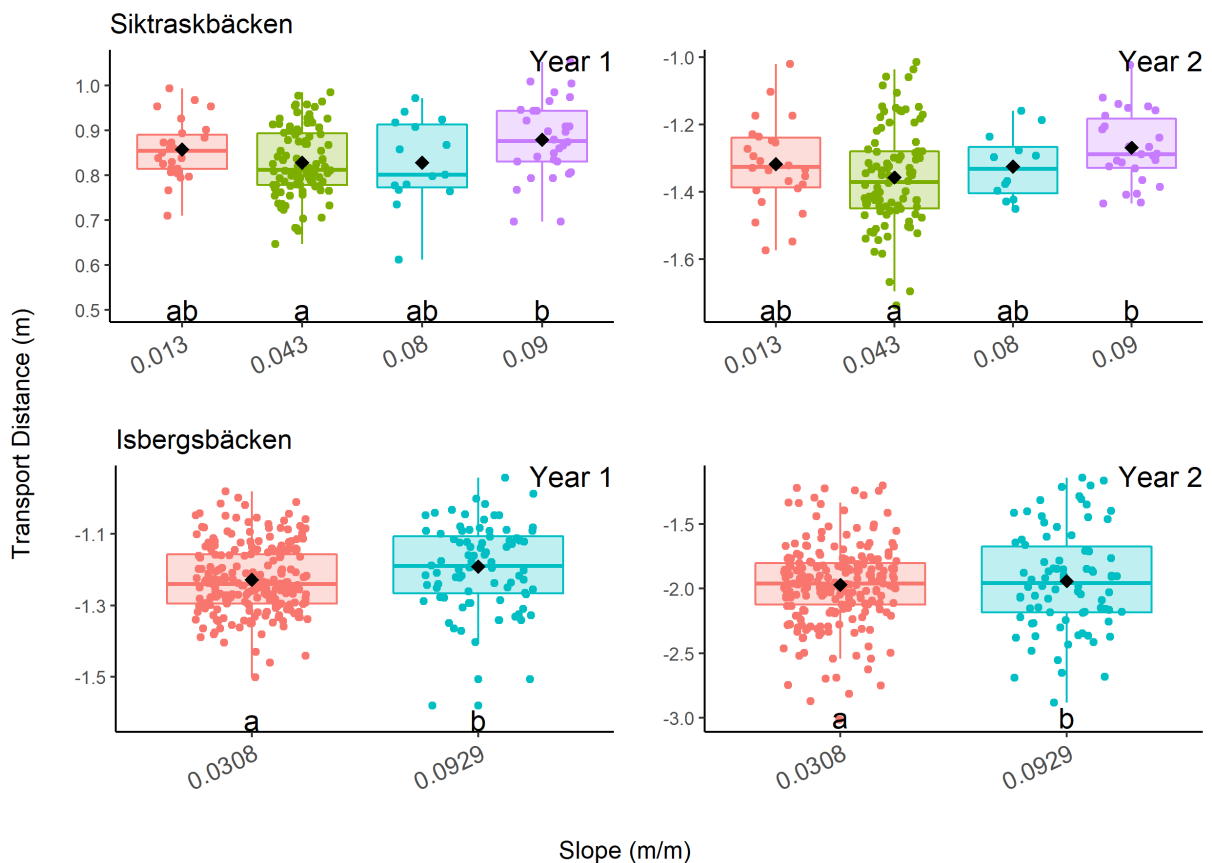


Figure 14: Box plot of the tracer transport distance (m) in function of the local bed slope (m/m). Letters below each plot shows significant pairwise differences in means ($P < 0.05$) (Tukey's HSD following ANOVA on Tukey transformed data). The box plots indicate upper and lower quartiles as box ends, 10th and 90th percentiles as whiskers, and median values as the line within each box.

3.7- Study of Shields parameter

This part aims to determine if the forecast of movement based on the comparison of the Shields parameter and critical Shields stress is verified or not. Thus, transport distance was plotted against the critical ratio (Fig. 15). If the ratio is greater than one, the transport distance is expected to be greater than 0.05m (smallest distance to consider a movement, taking into account the uncertainty on coordinates measurement). A coloration in R studio allows us to visualize in blue, tracers that moved further than 0.05m and in red, tracers considered as immobile. The red dashed line represents the threshold where the critical ratio is equal to 1. The critical Shields stress based on Lamb's equation ranged between 0.05 to 0.08 for Sikträskbäcken, 0.06 to 0.08 for Isbergsbäcken, and equaled to 0.06 in Mattjokkbäcken where a constant slope was considered for the calculation.

A significant number of tracers above the threshold did not move, this may be explained by an effect of the boulder observed by Yager et al. (E. M. Yager et al., 2007, 2012). Indeed, boulders can bear some shear stress and thus decrease the available shear stress for finer sediments that is why the general sediment transport equation would over-predict the sediment transport rates.

The three reaches have tracers with a critical ratio greater than one and yet no movement measured, especially in Isbergsbäcken and Sikträskbäcken. It is interesting to notice that Mattjokkbäcken is different, as almost all tracers moved the first year. This can indicate two things:

- The "unnatural" and random placement of the tracers created instabilities facilitating the movement so that the response is different from the two other rivers
- Past a certain "threshold" flow, the effect of shear stress "absorption" by the boulders becomes insignificant because even with the boulders effect, the flow is sufficient to move sediments.

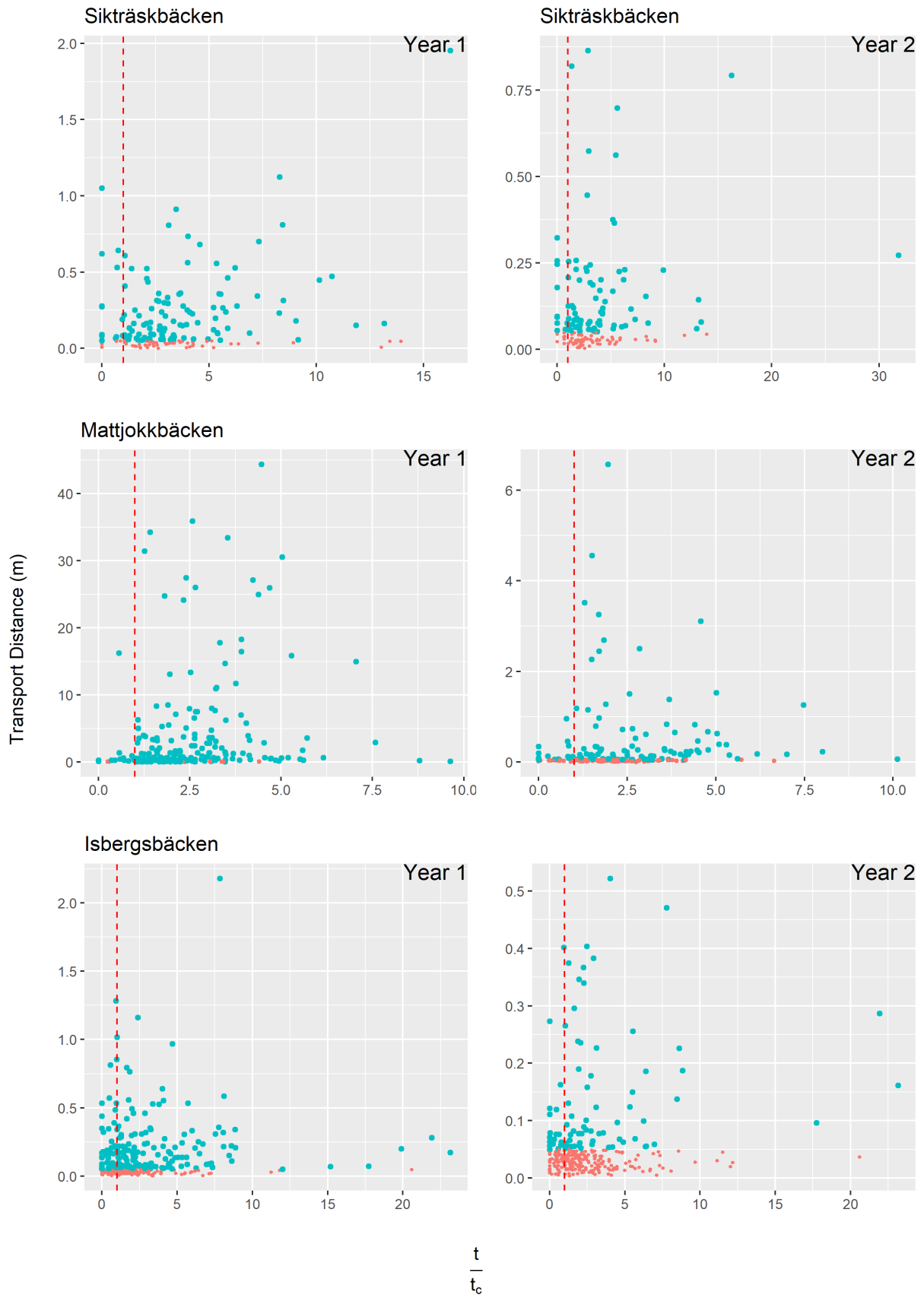


Figure 15:Transport Distance (m) in function of the critical ratio, Red dashed line represents the threshold were $RATIO > 1$ supposing an incipient movement, the red dots are grains with a transport distance $L < 0.05$ m which are considered as immobile.

Table 11 indicates the percentages of tracers that should be mobile, based on the fact that they have a critical ratio greater than 1. This table leads to different hypotheses. Indeed, we can first notice that in both Sikträskbäcken and Isbergsbäcken, the rate is not less than 29%, meaning that the prediction based on the calculation of the Shields parameter and the critical Shields stress overestimates sediment transport. Secondly, the second year the immobile tracers rate increases up to 52% in Isbergsbäcken which clearly shows that the incipient threshold does not predict well transport in this river, the same can be said for Sikträskbäcken.

Table 11: Percentages and number of tracers in immobile despite a critical ratio greater than 1

	Sikträskbäcken		Mattjokkbäcken		Isbergsbäcken	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Number of tracers recovered	169	158	208	197	314	311
Number of tracers with $L < 0.05$ & critical ratio > 1	49	66	8	64	93	163
Percentage of immobile tracer above the critical ratio (%)	29	42	3.8	32.4	29.6	52.4

Moreover, it is interesting to note that for the first year of the experiment in Mattjokkbäcken, only less than 4% of tracers did not follow the prediction against almost 10 times more the second year. Here it is hard to quantify whether it is only due to the unstable placement of tracers at the beginning of the experiment or because a high discharge occurred in 2018. A hypothesis, which would have to be tested for the following years would be that passed a certain return period of discharge, the impact of boulder becomes less important.

3.8- Results synthesis

Through this study, the obtained results seem to show that:

- The study of grains' size on transport did not show clear relation. It can rather work as a diameter threshold around 100mm under which tracers are very likely to move.
- The global morphology does not have a significant impact on transport
- The constraint class does not seem to control the transport as expected. Indeed, unconstrained class moved further only the first year which is not representative of natural condition. For the second year, no clear correlation could be found.
- The slope has a great influence on the transport, being positively correlated
- The prediction of incipient movement based on the critical Shields stress set at $\tau * _c = 0.15 \times S^{0.25}$ (after Lamb (2008)) does not reflect the reality of the transport on the field. Probably because of the shear stress absorbed by boulders
An important result concerns Mattjokkbäcken the first year, under a high discharge almost all tracers were mobile, which would suggest a threshold concerning discharge after which critical Shields stress is overcome
- The influence of boulders is not clear. By absorbing shear stress, they decrease the shear stress available for sediment to move. But it is not clear whether they have an area of influence, no significant difference concerning the transport distance was found between tracers close to boulders (<1m) and further ones.

4- DISCUSSION

4.1- High variability of sediment study in the field

First, this study reveals all empiric characters that can occur especially in geomorphology studies. Indeed, following tracers in a river is quite challenging, even if the recovery rate was high for those two first years of experiment, the variability of results was high. It reminds us that field study necessarily implies some sort of variability and the results can thus be not as clear as in flume study where major control parameters are set and followed over time (e.g. discharge, sediment rate, slope).

This also highlights two important limits of this study. First, only two years of data are available with one first year that is not really representative of the natural condition of sediments in the river. After some years, different flood can occur, and a certain stability will be found by the sediment. That is why it will be more consistent to analyze the data after a few more years to confirm the theory of high variability or maybe find out a pattern of control by boulders.

Secondly, the tracers' positions are measured only once a year because they are passive tracers and surveying all of them in all reaches takes a lot of time. It is surveyed after the spring flood, which is considered as the main factor of movement in the year, but it is possible that other hydraulic characteristics as ice formation have a high impact on transport. We could have imagined using for example active tracers, which would permit to follow the tracers over time. But active tracers also have their limits, for example, in terms of battery (which could be very problematic during the low temperature in winter and also in a matter of sustainability through time). This is limiting in terms of hydraulic analysis because it is then hard to associate a discharge to the movement. It could be interesting to study the transport based on the flow velocity or the stream power and not the shear stress and would probably lead to other conclusions as for steeper rivers (Yager et al., 2007).

4.2- Importance of the ice cover

As presented previously, the study area is part of the northern Borealis rivers, which implies the creation of ice formations during the winter. According to Lind, different ice formations can occur, as anchor ice and suspended ice (Lind, 2015). The first type, anchor ice, is constituted of frazil ice particles which is ice formed by supercooling water (water under 0°C). As its name indicates it anchor ice needs a surface to adhere on which it will develop and remain in the stream bed, that is why it is more likely to develop in boulder rivers. (Stickler & Alfredsen, 2009) Whereas suspended ice, designates ice formation floating on the water surface induced by the break of anchor ice dams.

Usually, it is assumed that only the discharge controls the flow. However, the qualitative importance of ice is well reported in the literature and recent, studies even tried to quantify the impact of ice. (Stickler et al., 2010)

Recently, a new technique to study ice cover and ice impacts has been developed in a Northern Sweden river, using the seismic principle to capture the ice breaking and possibly link it to flow events.

This technique is still under development but it could be coupled to this study to quantify ice breaking effects. It should then be necessary to survey more than once the tracers or even use active tracers.

4.3- Limits of the calculation

The study in the field could gain in precision, especially in the boulder's size characterization. Indeed, their representation in ArcGIS was approximated by considering each boulder as circular objects. It must have led to some errors when calculating the distance to boulders for example. Also, the tracers' transport was considered linear between two years, but actually it could be more complex with back and forth or lateral movements. This calculation approximation is linked to the annual survey and would require more data collects to be more accurate.

Another limit would be the number of tracers. Sometimes a certain type of constraint or global morphology could be attributed to less than 5 tracers, this cannot really be taken into account in the statistical analysis and thus decrease the knowledge on those classes.

Finally, concerning the study of constraint class, it should not be forgotten that only one survey per year is done on tracers, this limits the information given by this class. Indeed, it could totally be possible that after being in the observed classes of constraint, they moved to others different classes making the interpretation of data more complex.

CONCLUSION

This study based on passive tracers shows the high variability in results when speaking of field experiment. Identifying a clear pattern of sedimentation is difficult because of the high interaction between each parameter. No fixed or controllable parameter can be set as in a flume study for example, making it more difficult to identify and quantify the part of each parameter on the sediment transport.

This first study on two years of results allows us to have an overview of the sediment transport, and confirmed that the protocol used to monitor the tracers is efficient with a high recovery rate. Even if no linear correlation link grain size and transport distance, grain size appears to be important, but more in the form of a threshold size at which transport would be less important in terms of distance and frequency. The influence of global morphology as step-pool or planebed was not significant but could still be followed in the future to collect more data to analyze. The constraint class followed the hypothesis emitted but only for the first year of experiment. Indeed, the unconstrained class in year 1 had a greater transport distance for Sikträskbäcken and Isbergsbäcken. But surprisingly, the second year, buried class were the one that moved further.

This study also reveals the high variability induced by boulders, with no clear pattern but some hydraulic perturbations leading to variability concerning the sediment transport. And confirmed the positive correlation of the slope with sediment transport. Furthermore, by comparing the empirical movement of tracers to a forecast incipient motion, we can conclude that the equation suggested by Lamb is not efficient to predict the movement in those type of river.

Having only two years of experiment including one year not really representative of the process in natural condition limits the significance of the study. However, it is important to keep monitoring the rivers to see how it will evolve in the future.

On a more practical and methodological extent, this study installed instruments to process data with the elaboration of R scripts to test ANOVA or different correlation.

REFERENCES

- Buffington, J. M., & Montgomery, D. R. (2013). 9.36 Geomorphic Classification of Rivers. In *Treatise on Geomorphology* (p. 730-767). Elsevier. <https://doi.org/10.1016/B978-0-12-374739-6.00263-3>
- Camenen, B., Coz, J. L., Paquier, A., & Lagouy, M. (s. d.). *An estimation of gravel mobility over an alpine river gravel bar (Arc en Maurienne, France) using PIT-tag tracers*. 9.
- Charlton, R. (2007). *Fundamentals of Fluvial Geomorphology*. Routledge.
- Church, M. (2006). BED MATERIAL TRANSPORT AND THE MORPHOLOGY OF ALLUVIAL RIVER CHANNELS. *Annual Review of Earth and Planetary Sciences*, 34(1), 325-354. <https://doi.org/10.1146/annurev.earth.33.092203.122721>
- Church, M., Biron, P., & Roy, A. (2012). *Gravel Bed Rivers : Processes, Tools, Environments*. John Wiley & Sons.
- Hassan, M. A., & Bradley, D. N. (2017). Geomorphic Controls on Tracer Particle Dispersion in Gravel-Bed Rivers. In *Gravel-Bed Rivers* (p. 159-184). John Wiley & Sons, Ltd. <https://doi.org/10.1002/9781118971437.ch6>
- Hassan, M. A., Church, M., Lisle, T. E., Brardinoni, F., Benda, L., & Grant, G. E. (s. d.). SEDIMENT TRANSPORT AND CHANNEL MORPHOLOGY OF SMALL, FORESTED STREAMS. *JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION*, 24.
- Hellström, G., Palm, D., Brodin, T., Rivinoja, P., & Carlstein, M. (2019). Effects of boulder addition on European grayling (*Thymallus thymallus*) in a channelized river in Sweden. *Journal of Freshwater Ecology*, 34(1), 559-573. <https://doi.org/10.1080/02705060.2019.1614102>
- Huusko, A., Greenberg, L., Stickler, M., Linnansaari, T., Nykänen, M., Vehanen, T., Koljonen, S., Louhi, P., & Alfredsen, K. (2007). Life in the ice lane : The winter ecology of stream salmonids. *River Research and Applications*, 23(5), 469-491. <https://doi.org/10.1002/rra.999>
- Lamarre, H., MacVicar, B., & Roy, A. G. (2005). Using Passive Integrated Transponder (PIT) Tags to Investigate Sediment Transport in Gravel-Bed Rivers. *Journal of Sedimentary Research*, 75(4), 736-741. <https://doi.org/10.2110/jsr.2005.059>

- Lamarre, H el ene, & Roy, A. G. (2008). The role of morphology on the displacement of particles in a step–pool river system. *Geomorphology*, 99(1-4), 270-279.
<https://doi.org/10.1016/j.geomorph.2007.11.005>
- Lamb, M. P., Dietrich, W. E., & Venditti, J. G. (2008). Is the critical Shields stress for incipient sediment motion dependent on channel-bed slope? *Journal of Geophysical Research*, 113(F2), F02008.
<https://doi.org/10.1029/2007JF000831>
- Lambeck, K., Smither, C., & Johnston, P. (1998). Sea-level change, glacial rebound and mantle viscosity for northern Europe. *Geophysical Journal International*, 134(1), 102-144.
<https://doi.org/10.1046/j.1365-246x.1998.00541.x>
- Lenzi, M. A., D'Agostino, V., & Billi, P. (1999). *Bedload transport in the instrumented catchment of the Rio Cordon Part I: Analysis of bedload records, conditions and threshold of bedload entrainment*. 21.
- Lind, L. (s. d.). *Effects of ice formation and winter floods on vegetation along streams*. 35.
- Luzi, D. S. (2014). *Sediment transport and morphological response of a semi-alluvial channel : Insights from a Froude scaled laboratory model*. <https://doi.org/10.14288/1.0165910>
- Masteller, C. C., & Finnegan, N. J. (2017). Interplay between grain protrusion and sediment entrainment in an experimental flume : GRAIN PROTRUSION AND SEDIMENT ENTRAINMENT. *Journal of Geophysical Research: Earth Surface*, 122(1), 274-289. <https://doi.org/10.1002/2016JF003943>
- Meshkova, L. V., Carling, P. A., & Buffin-B elanger, T. (2012). Nomenclature, Complexity, Semi-Alluvial Channels and Sediment-Flux-Driven Bedrock Erosion. In M. Church, P. M. Biron, & A. G. Roy ( eds.), *Gravel-Bed Rivers* (p. 424-431). John Wiley & Sons, Ltd.
<https://doi.org/10.1002/9781119952497.ch31>
- Meyer-Peter, E., & M uller, R. (1948). Formulas for Bed-Load transport. *IAHSR 2nd Meeting, Stockholm, Appendix 2*. <https://repository.tudelft.nl/islandora/object/uuid%3A4fda9b61-be28-4703-ab06-43cdc2a21bd7>
- Monsalve, A., Yager, E. M., & Schmeeckle, M. W. (2017). Effects of Bed Forms and Large Protruding Grains on Near-Bed Flow Hydraulics in Low Relative Submergence Conditions : Effects of Bed Forms on

- Near-Bed Flow. *Journal of Geophysical Research: Earth Surface*, 122(10), 1845-1866.
<https://doi.org/10.1002/2016JF004152>
- Nilsson, C., Sarneel, J. M., Palm, D., Gardeström, J., Pilotto, F., Polvi, L. E., Lind, L., Holmqvist, D., & Lundqvist, H. (2017). How Do Biota Respond to Additional Physical Restoration of Restored Streams? *Ecosystems*, 20(1), 144-162. <https://doi.org/10.1007/s10021-016-0020-0>
- Palm, D. (s. d.). *Restoration of streams used for timber floating : Egg to fry survival, fry displacement, overwintering and population density of juvenile brown trout (Salmo trutta L.)*. 32.
- Papangelakis, E., & Hassan, M. A. (2016). The role of channel morphology on the mobility and dispersion of bed sediment in a small gravel-bed stream : Role of morphology on the mobility and dispersion of bed sediment. *Earth Surface Processes and Landforms*, 41(15), 2191-2206.
<https://doi.org/10.1002/esp.3980>
- Papanicolaou, A. N. (Thanos), Tsakiris, A. G., Wyssmann, M. A., & Kramer, C. M. (2018). Boulder Array Effects on Bedload Pulses and Depositional Patches. *Journal of Geophysical Research: Earth Surface*, 123(11), 2925-2953. <https://doi.org/10.1029/2018JF004753>
- Papanicolaou, A. (Thanos) N., Dermisis, D. C., & Elhakeem, M. (2011). Investigating the Role of Clasts on the Movement of Sand in Gravel Bed Rivers. *Journal of Hydraulic Engineering*, 137(9), 871-883.
[https://doi.org/10.1061/\(ASCE\)HY.1943-7900.0000381](https://doi.org/10.1061/(ASCE)HY.1943-7900.0000381)
- Parker, G., Seminara, G., & Solari, L. (2003). Bed load at low Shields stress on arbitrarily sloping beds : Alternative entrainment formulation. *Water Resources Research*, 39(7).
<https://doi.org/10.1029/2001WR001253>
- Piégay, H., Arnaud, F., Cassel, M., Dépret, T., Alber, A., Michel, K., Rollet, A.-J., & Vaudor, L. (s. d.). *SUIVI PAR RFID DE LA MOBILITÉ DES GALETS : RETOUR SUR 10 ANS D'EXPÉRIENCE EN GRANDES RIVIÈRES*. 16.
- Piton, G. (s. d.). *Méthode de transfert de bassin*. 3.
- Polvi, L. E., Nilsson, C., & Hasselquist, E. M. (2014). Potential and actual geomorphic complexity of restored headwater streams in northern Sweden. *Geomorphology*, 210, 98-118.
<https://doi.org/10.1016/j.geomorph.2013.12.025>

- Shamloo, H., Rajaratnam, N., & Katopodis, C. (2001). Hydraulics of simple habitat structures. *Journal of Hydraulic Research*, 39(4), 351-366. <https://doi.org/10.1080/00221680109499840>
- Shields, A. (1936). *Application of similarity principles and turbulence research to bed-load movement* [Report or Paper]. California Institute of Technology.
<https://resolver.caltech.edu/CaltechKHR:HydroLabpub167>
- Stickler, M., & Alfredsen, K. T. (2009). Anchor ice formation in streams : A field study. *Hydrological Processes*, 23(16), 2307-2315. <https://doi.org/10.1002/hyp.7349>
- Stickler, M., Alfredsen, K. T., Linnansaari, T., & Fjeldstad, H.-P. (2010). The influence of dynamic ice formation on hydraulic heterogeneity in steep streams. *River Research and Applications*, 26(9), 1187-1197. <https://doi.org/10.1002/rra.1331>
- Ume- och Vindelälvens Vattenvårdsförbund. (s. d.). Consulté 15 juin 2020, à l'adresse
<http://www.umevindelvff.se/>
- Vattenwebb—Modelldata per område. (s. d.). Consulté 18 juin 2020, à l'adresse
<https://vattenwebb.smhi.se/modelarea/>
- Vindel River LIFE. (s. d.). Consulté 15 juin 2020, à l'adresse <http://vindlriverlife.se/?lang=en>
- Yager, E. M., Kirchner, J. W., & Dietrich, W. E. (2007). Calculating bed load transport in steep boulder bed channels : SEDIMENT TRANSPORT IN STEEP CHANNELS. *Water Resources Research*, 43(7).
<https://doi.org/10.1029/2006WR005432>
- Yager, E. M., Turowski, J. M., Rickenmann, D., & McArdeell, B. W. (2012). Sediment supply, grain protrusion, and bedload transport in mountain streams : SEDIMENT SUPPLY AND BEDLOAD TRANSPORT. *Geophysical Research Letters*, 39(10), n/a-n/a.
<https://doi.org/10.1029/2012GL051654>
- Yager, Elowyn M., Schmeeckle, M. W., & Badoux, A. (2018). Resistance Is Not Futile : Grain Resistance Controls on Observed Critical Shields Stress Variations. *Journal of Geophysical Research: Earth Surface*, 2018JF004817. <https://doi.org/10.1029/2018JF004817>

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1. INTRODUCTION

1.1- Contexte

Historiquement, les études hydrogéomorphologiques se sont attachées à caractériser l'évolution des morphologies des rivières, en suivant notamment le transport sédimentaire qui impacte directement la texture du lit et ainsi les habitats écologiques. (Hassan & Bradley, 2017) Au fil des années la caractérisation du transport sédimentaire a progressé notamment avec l'introduction de traceurs actifs et passifs dans les études de terrain (H. Lamarre et al., 2005; Piégay et al., 2016), ainsi que le développement des expériences en laboratoire. Cependant, si l'on tient compte du lien étroit entre chaque rivière et son environnement : selon le climat, le passé géologique, etc., il en ressort une grande diversité de type de rivières. Chaque rivière nécessiterait ainsi une étude ciblée pour comprendre ses mécanismes géomorphologiques. Même si des éléments morphologiques peuvent être communs à différents faciès de rivières, avec par exemple les lits rocheux présents aussi bien en rivières de montagne qu'en rivières semi-alluviales, d'autres paramètres tels que la pente ou le débit peuvent grandement varier. C'est pourquoi, il est important de considérer chaque rivière comme un tout lors d'une étude de transport sédimentaire.

Selon Hassan, malgré les récents progrès technologiques concernant le suivi sédimentaire, les études de terrain s'intéressent généralement uniquement à des paramètres simples tels que la vitesse et la distance de transport (Hassan & Bradley, 2017). Alors que les études en canal artificiel permettent de contrôler l'environnement d'étude, et ont ainsi été très utilisés pour comprendre les processus sédimentaires, notamment les interactions avec la morphologie du cours d'eau, la pente, ainsi que les éléments immobiles du lit tels que les blocs rocheux. (Masteller & Finnegan, 2017; Papanicolaou et al., 2018) Durant ces dernières décennies, des études se sont intéressées à l'impact des blocs dans le lit sur le courant et la contrainte de cisaillement. Des motifs distincts de sédimentation ont pu être identifiés, mais ces études ont surtout été menées en canal artificiel ou sur des rivières différentes des rivières semi-alluviales.

C'est pourquoi, les processus sédimentaires dans les rivières semi-alluviales restent globalement méconnus. Comprendre avec précision l'interaction des blocs rocheux avec la rivière est d'autant plus important que ce type de rivière est majoritaire dans le Nord de la Suède.

1.2- Caractéristiques des rivières semi-alluviales

L'appellation rivière « semi-alluviale » définit de manière générale une rivière alluviale avec des éléments solides contraignant la rivière. Cela signifie que la rivière peut soit être confinée entre des « murs latéraux » ou que le lit peut être constitué de roche. (Meshkova et al., 2012) Mais cette définition peut être étendue aux rivières présentant de larges éléments immobiles déposés par des processus non alluviaux (Fig. 16).

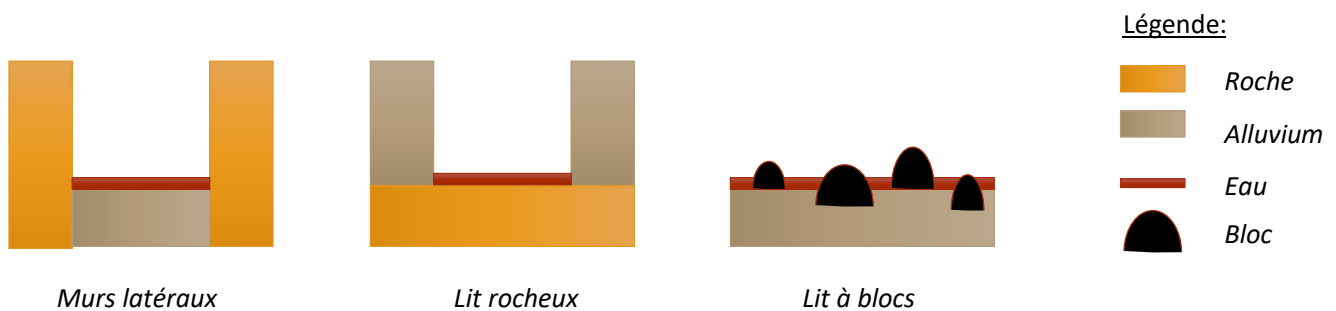


Figure 16: Les différents types de rivières semi-alluviales (inspiré de Meshkova, 2014)

Ces éléments grossiers peuvent être un héritage de la glaciation continentale, grâce à des processus géologiques tels que les moraines, eskers ou encore erratiques (Polvi et al., 2014). Comme ces blocs ont été introduits par des processus géomorphologiques anciens non alluviaux comme la glaciation, des débits même importants ne peuvent pas déplacer ces éléments. Ils représentent des points d'ancrage dans les rivières.

Si d'une part, à travers des années d'études, une meilleure connaissance générale des rivières alluviales a été atteinte, en caractérisant la réaction des chenaux en fonction notamment de leurs géométries. (Church, 2006; Luzi, 2014) D'autre part, les rivières semi-alluviales ont très peu été étudiées. Même si, des études en canaux artificiels et sur le terrain se sont attachées à déterminer des motifs de sédimentation, il est nécessaire de différencier les résultats selon le type de rivière semi-alluviale. Une rivière à lit rocheux n'aura certainement pas la même dynamique qu'une rivière avec une contrainte latérale. De plus, la répartition aléatoire des blocs dans le lit de la rivière rend d'autant plus difficile la prédiction de la réponse sédimentaire d'une rivière à l'autre. Avec par exemple, différents effets sur l'hydraulique du cours d'eau selon la densité de blocs et leur disposition. (Papanicolaou et al., 2011)

1.3- Historique lié à l'industrie du bois et projets de restauration des rivières

Historiquement, le Nord de la Suède est connu pour son industrie du bois, c'est pourquoi les rivières ont eu une importance majeure, puisque utilisées dans le transport du bois à travers le pays. Des années 1800 à 1976, de nombreuses rivières comme Mattjokkbäcken ont ainsi subi des transformations pour faciliter le transport du bois. Notamment en déplaçant les blocs rocheux du lit vers les berges (*Vindel River LIFE*, s. d.). Les rivières plus petites et plus pentues comme Sikträskbäcken et Isbergsbäcken n'ont pas pu être utilisées et sont ainsi restées dans un état « naturel ».

Depuis les années 1870, une volonté de restauration des rivières a émergé dans le pays, pour améliorer l'état écologique des rivières, et augmenter les habitats de poissons en réintroduisant des éléments rocheux. En 2010, un projet européen LIFE, nommé Vindel River Life (*Vindel River LIFE*, s. d.) a été initié et vise à tester une nouvelle méthode de restauration, en prenant en compte l'importance des blocs dans ces rivières semi-alluviales fenno scandinaves. En plus de l'ajout de sédiments grossiers, ils ont également réouvert les rivières en déplaçant les blocs (de diamètre 1 à 2m) des berges vers le lit des cours d'eau (Polvi et al., 2014). L'idée étant d'augmenter l'hétérogénéité morphologique des rivières dans le but d'augmenter la diversité écologique. Mais comme l'effet des blocs sur le courant reste très peu connu, ces restaurations restent un processus expérimental.

Ce projet s'est terminé en 2015, et des études ont depuis mesuré l'impact des restaurations en comparant l'évolution des complexités morphologiques avant et après restauration. (Hellström et al., 2019; Nilsson et al., 2017; Polvi et al., 2014) Même si aucune différence significative n'a encore été observée, les auteurs rappellent que les processus écologiques nécessitent du temps et qu'il est donc important de suivre leur évolution et de ne pas s'arrêter sur ces premières observations.

Un autre aspect important des blocs dans l'écologie des rivières concerne leur rôle durant l'hiver. En effet, des études ont montré que les salmonidés peuvent utiliser les blocs comme des abris durant l'hiver. Aussi, les blocs facilitent la formation de glace de fond (anchor ice), cette dernière peut également être utilisée par certaines espèces pendant la période hivernale. (Husko et al., 2007)

Quantifier les résultats des restaurations est nécessaire pour améliorer les méthodes utilisées. Mais comprendre les processus de transport de sédimentaire dans les rivières semi-alluviales à blocs rocheux pourrait réduire significativement l'incertitude des restaurations, qui restent pour l'instant expérimentales avec une répartition aléatoire des blocs. La partie suivante condense les connaissances en matière de transport sédimentaire acquises au cours des dernières années.

1.4- Contrôles géomorphologiques du transport sédimentaire

1.4.1- CONTROLES SEDIMENTAIRES LIES AU FACIES DU LIT

Le transport sédimentaire a largement été étudié à travers un bilan des forces motrices et des forces de résistance pour établir un seuil de mise en mouvement appelé contrainte de cisaillement critique (τ_c^*). Différents paramètres contrôlent le transport sédimentaire : la vitesse du courant, la pente en lien avec la force de gravité exercée, la protrusion des blocs et leur nombre créant des forces de trainée, la taille et la forme du grain sur lequel ces forces s'appliquent ainsi que les forces de frottements et la poussée d'Archimède.

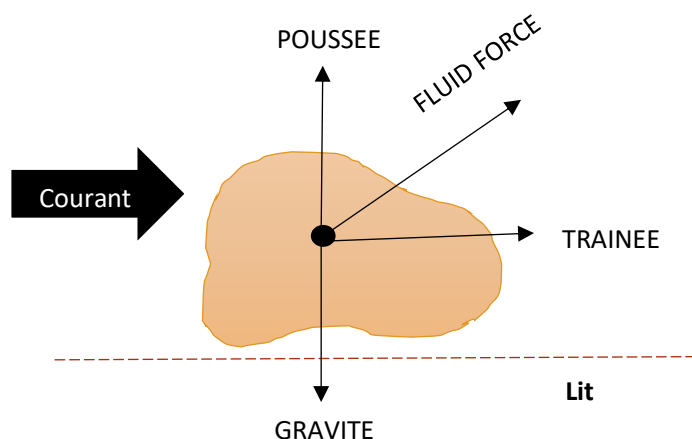


Figure 17: Bilan des forces exercées sur une particule (tiré de Ro Charlton, 2007)

- **Morphologie du cours d'eau :**

Au sein d'un tronçon, une rivière peut présenter une alternance de différentes morphologies comme par exemple : des formations en step-pool, riffles-pool, plane-bed, etc. Ceci influençant notamment la hauteur d'eau et donc le régime hydraulique ce qui influencera le transport sédimentaire. Quantifier précisément l'impact que produit la morphologie d'une rivière sur le transport sédimentaire reste difficile. Notamment parce que le transport sédimentaire est à la base de la création des différentes morphologies, qui à leur tour influencent le transport sédimentaire. Cependant, plusieurs études ont montré le contrôle exercé par les différents faciès sur le transport sédimentaire et ont même essayé de le quantifier. (Hassan et al., s. d.; Hélène Lamarre & Roy, 2008; Papangelakis & Hassan, 2016) Buffington & Montgomery ont identifié différentes classes de morphologies couramment présentes dans les cours d'eau, et détaillées ci-dessous:

- Step-pool: Aussi appelé « marche-cuvette » en français, cela correspond généralement à une alternance de marches et de fosses de creusement. Au niveau des marches, une rupture abrupte de la pente dans le lit entraîne une augmentation locale de la vitesse du

courant. C'est pourquoi il s'agit d'une formation morphologique avec une grande capacité hydraulique de transport notamment pour les graviers et les fines particules.

- Riffle-pool: Aussi appelé « seuil-mouille », les seuils ou rides se forment dans les zones peu profondes, contenant généralement des matériaux plus grossiers. Alors que les mouilles sont plus profondes et plus calmes. Les contraintes de cisaillement du lit dans les mouilles sont plus élevées que dans les seuils en raison des sédiments plus grossiers, ce qui augmente la résistance locale du lit.
- Plane-bed: Contrairement aux formations de type riffle-pool et step-pool, cette morphologie est moins complexe, car ne présente pas de caractéristique spécifique. La capacité de transport y est donc plus faible qu'au niveau d'une step-pool.

- **Pente :**

L'effet de la pente sur la stabilité d'un grain peut être vu de deux manières. Tout d'abord, il semble logique de penser qu'une pente forte crée davantage de déséquilibre en augmentant la force de gravité exercée sur le grain. Mais, d'un autre côté, Lamb a montré que le cisaillement critique est positivement corrélé à la pente. Ceci implique que plus la pente est élevée plus le cisaillement critique est grand et donc plus la particule nécessitera de force pour être mise en mouvement. (Lamb et al., 2008)

- **Blocs rocheux**

D'un point de vue hydraulique, un bloc isolé dans le lit représente un obstacle pour le courant et constitue donc une perturbation. Un bloc complètement immergé crée une décélération en amont au niveau de la couche d'eau proche du lit et induit un mouvement de contre-courant à l'aval directe du bloc appelé en anglais « near-wake ». Enfin, plus loin à l'aval, un autre type de vague est observé appelé « far-wake » associée à une décélération (Shamloo et al., 2001). Il a été démontré que les blocs rocheux « absorbent » de la force de cisaillement et diminuent ainsi la contrainte disponible au travers des forces de traînées. (Yager et al., 2007) De plus, la répartition dans l'espace des blocs rocheux a une grande importance dans le transport sédimentaire. En effet, en fonction de leur répartition et leur prééminence, différentes perturbations hydrauliques peuvent être observées. (Papanicolaou et al., 2011)

Un autre paramètre important dans l'étude de l'influence des rochers est la profondeur relative H/d_{prot} où H est la profondeur et d_{prot} la hauteur de saillie des rochers (Papanicolaou & Kramer, 2006 ; Shamloo et al., 2001). Shamloo et al. (2001) ont identifié quatre régimes différents en fonction de cette profondeur relative. Mais dans la pratique, les études se sont concentrées uniquement sur la faible submersion relative (LRS) qui se produit pendant les épisodes de faible débit où H/d_{prot} est inférieur à un ($H/d_{\text{prot}} < 1$). Dans cette configuration, le rocher dépasse le niveau de l'eau et crée un fort régime de contre-courant derrière l'obstacle.

Et au contraire, la submersion à fort débit (HRS), où H/d_{prot} est supérieur à trois ($H/d_{\text{prot}} > 3$), se produit dans des conditions de fort débit dans notre cas lorsque la neige fond au printemps. (Papanicolaou et al., 2018) Dans ce cas, les blocs n'ont pas d'impact sur l'eau de surface mais créent quand même un tourbillon directement derrière celle-ci.

Ce régime de submersion différent conduit à des structures de tourbillons différentes, avec plus de reflux à LRS qu'à HRS. Une augmentation de la contrainte de cisaillement du lit autour du bloc rocheux a également été constatée (Shamloo et al., 2001). De plus, Monsalve (2017) a remarqué que dans les rivières de montagne, pour un faible taux de submersion, la contrainte de cisaillement moyenne ne repose plus sur la hauteur d'eau ou la pente mais plutôt sur la proéminence des blocs. (Monsalve et al., 2017)

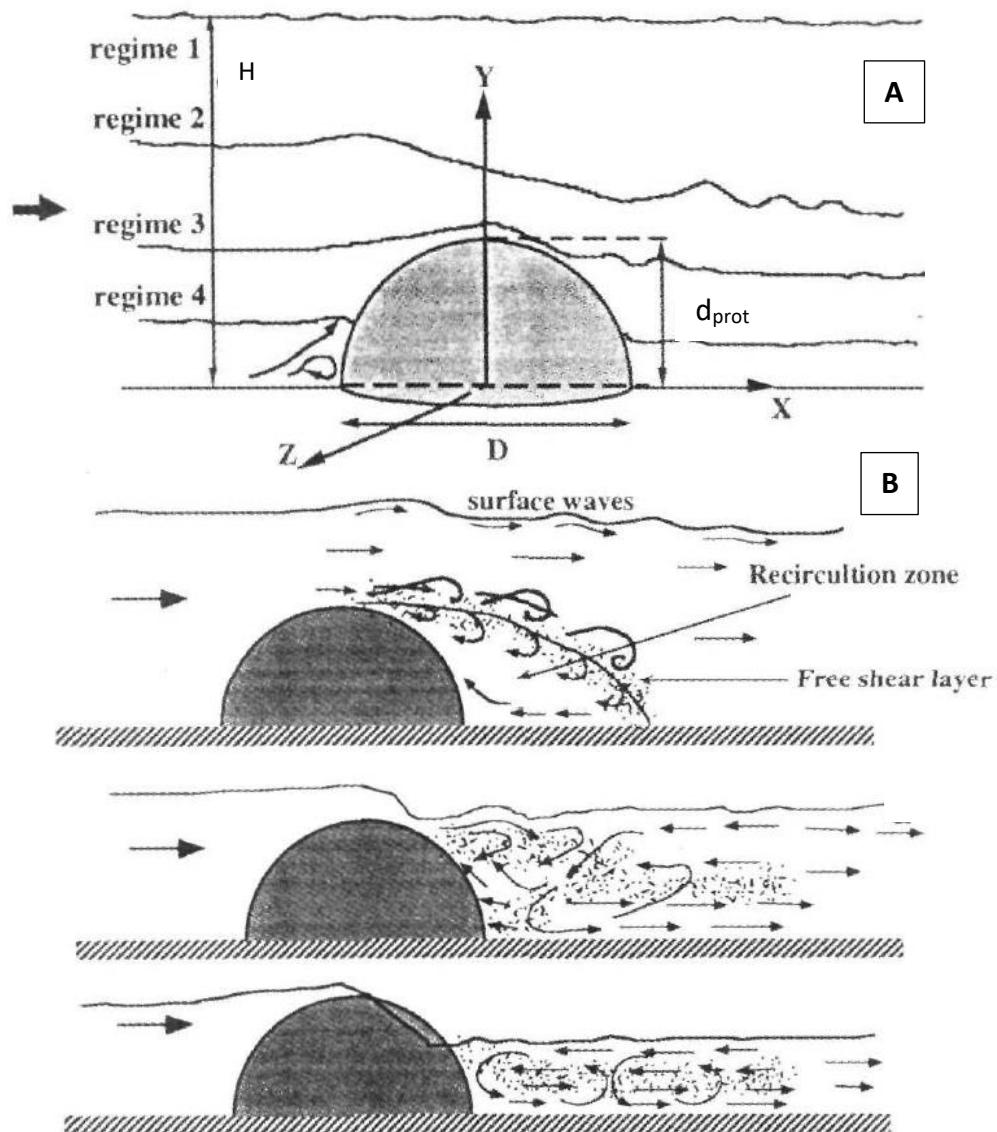


Figure 18: Régimes hydrauliques aux abords d'un bloc rocheux (d'après Shamloo et al., 2001), A : tirants d'eau pour différents régimes classés de 1 à 4 autour d'un bloc isolé, B : remous produits pour les régimes 2 à 4 (de haut en bas)

1.4.2- INFLUENCE DE LA TAILLE ET FORME DU SEDIMENT

Des années de recherche ont visé à trouver une corrélation entre le transport et la taille et forme des sédiments (Charlton, 2007). La figure 19 montre bien l'importance de la taille du grain car chaque force appliquée sur une particule est nécessairement dépendante de ce paramètre.

Pour avoir une vision complète des forces présentées en figure 17, il est intéressant de penser le grain non plus comme une particule isolée mais comme un élément évoluant dans un milieu hétérogène en sédiments et en structure. Ainsi, de nombreuses interactions vont avoir lieu entre différents sédiments de différentes tailles. Par exemple, un sédiment grossier peut abriter un sédiment plus fin le rendant alors moins mobilisable par le courant (shielded). Le sédiment peut également se retrouver imbriqué au milieu d'autres sédiments (imbricated). Lorsqu'un sédiment se retrouve partiellement enterré et pavé dans le lit on le qualifiera « d'embedded », alors que lorsqu'il se retrouve complètement recouvert de matière dans le lit il sera caractérisé d'enterré (buried).

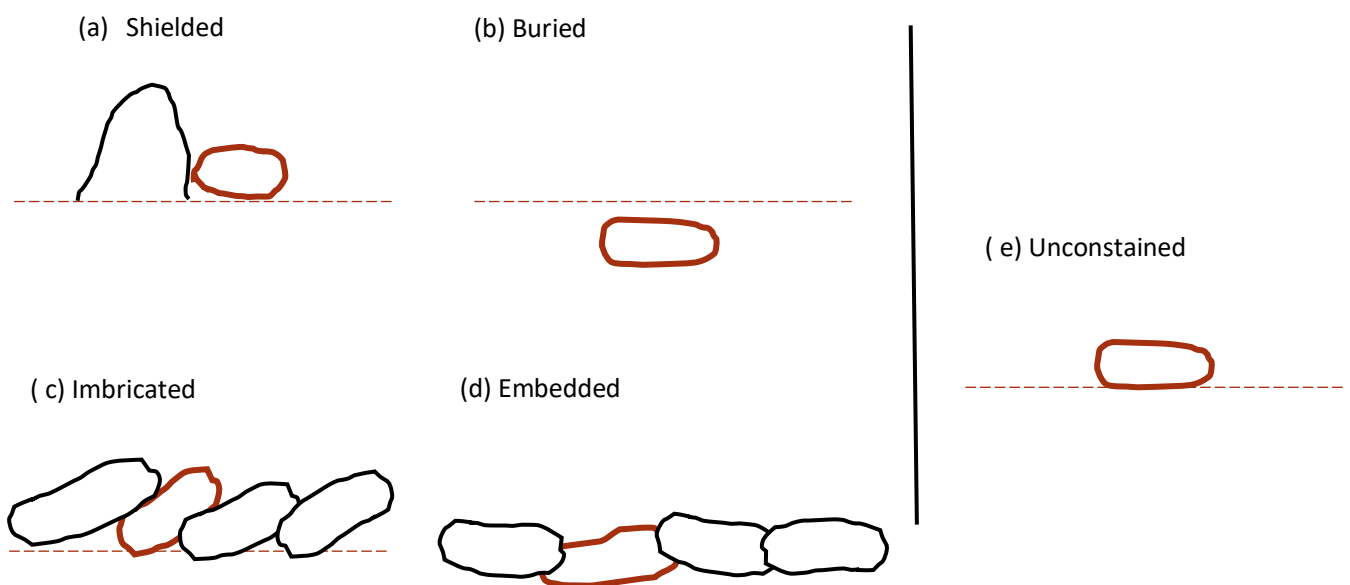


Figure 19: Représentation schématique des différentes classes de contrainte d'un sédiment ; avec de (a) à (d) les formes contraintes et (e) non contrainte

Suite aux différentes études sédimentaires, deux grandes idées ont été introduites concernant l'influence de la taille du grain sur son transport :

-le Size-Selective Transport (SST), autrement dit l'idée d'un transport sélectif en fonction de la taille du grain. Ceci a été présenté par Shields, cette théorie permet de déterminer un seuil de mise en mouvement en fonction du diamètre du grain. (Shields, 1936)

-le « Equal Mobility Transport » (EMT), cette approche suggère que la mise en mouvement d'une particule n'est pas dépendante de sa taille. Ainsi il vient :

$$\tau_c^* = \tau_{50}^* \times \left(\frac{D_i}{D_{50}}\right)^{-w}$$

Avec w un coefficient appelé facteur de masquage. Ainsi, un w proche de 1 indique un EMT car $\tau_c^* D_i = \tau_{50}^* D_{50}$ et donc le comportement d'une particule de diamètre D_i serait comparable à celui d'une particule de diamètre D_{50} . Et au contraire pour des w plus petits, le transport sera du type SST. De plus, il peut être considéré que passé des forts débits ou lorsque la contrainte de cisaillement est importante, le transport sera du type EMT (Charlton, 2007). Au contraire, si la contrainte de cisaillement ou le débit sont en dessous des conditions d'entraînement, le transport sera alors plutôt du type sélectif. (Lenzi et al., 1999).

1.4.3- ETAT DE L'ART EN MATIERE DE CALCUL DU MOUVEMENT

Depuis le début des études de transport sédimentaire, l'enjeu principal consistait à trouver un seuil de début de mouvement des sédiments. Ce seuil est représenté par le paramètre appelé contrainte de cisaillement critique adimensionnalisée. Historiquement, Shields a suggéré un seuil critique $\tau_c^* = 0.06$, mais compte tenu de la grande diversité des types de rivières avec différents régimes hydrauliques, types de lits, etc., il semble impossible d'avoir un seuil unique. De plus, d'autres auteurs ont proposé par la suite d'autres valeurs seuils, ceci sera développé dans la partie 2.3.3. Même si cette valeur fixe peut donner une première idée du mouvement, il reste à déterminer le seuil le plus représentatif possible par rapport aux caractéristiques géodynamiques de la rivière étudiée. Une première approche consiste à calculer le bilan des forces exercées sur les particules comme expliqué dans la partie précédente.

Mais cette méthode omet encore l'ensemble des interactions des particules avec le lit, car elle ne prend pas en compte l'interaction avec les autres particules (telle qu'elle est introduite dans la section 1.4.2). Cela comprend par exemple l'effet de blindage et l'enfouissement plus ou moins profond dans le lit (Elwyn M. Yager et al., 2018). Pourtant ces derniers ont un contrôle significatif sur les particules. Yager (2018), a alors proposé d'introduire la prééminence des blocs (p) et l'effet de frottement intergranulaire. Il a déterminé que négliger ainsi ces deux paramètres conduit à sous-estimer significativement la contrainte de cisaillement critique et donc à surestimer le transport sédimentaire. Cette étude visant à inclure l'effet de la friction dans l'équation est encore très récente, mais de plus en plus d'études cherchent maintenant à caractériser plus précisément la mise en mouvement de manière quantitative.

1.5- Objectifs de l'étude

Sachant que les rivières semi-alluviales et surtout les rivières de Fennoscandie sont encore très peu étudiées et connaissant l'importance des blocs rocheux dans une rivière, il est essentiel de s'intéresser aux mécanismes sédimentaires qui agissent sur ces rivières. Surtout dans le contexte actuel de volonté de restauration des rivières. En effet, ces mesures de restauration visent à reproduire l'ancienne morphologie des rivières en réintroduisant des blocs au milieu de la rivière, mais le processus est encore très expérimental avec une répartition aléatoire des blocs. Dans le cadre de l'étude MorphoRest, qui suit 5 différents tronçons d'affluents des rivières Vindel et Ume, j'ai étudié

le transport sédimentaire de 3 tronçons. Deux n'ont pas été modifiés par l'industrie du bois : Sikträskbäcken et Isbergsbäcken et un autre faisant partie d'un programme de restauration tel que décrit au point 1.2 : Mattjokkbäcken. Mon stage a pour but de comprendre le transport des sédiments de ces rivières semi-alluviales à forte densité de blocs afin de fournir à terme des lignes directrices pour la restauration des rivières.

Pour déterminer les principaux facteurs contrôlant le transport sédimentaire, les hypothèses ci-dessous sont émises :

- Les résultats devraient montrer une différence entre la première et la deuxième année liée au positionnement instables des traceurs dans les rivières
- Le transport dépend de la taille du grain et de la pente. Un grain plus gros nécessitera une contrainte de cisaillement plus forte pour le mobiliser. Une pente plus forte induirait un Shields critique plus important
- Les traceurs non contraints devraient avoir un transport plus important
- Les traceurs proches de blocs rocheux (à moins de 1-2m) auront une distance de transport plus petite que ceux plus éloignés
- Le transport sera différent selon que le traceur est situé en amont, en aval ou à côté d'un bloc rocheux
- Les traceurs placés sur des « step » devraient être plus mobilisés

7.2- Traduction française de la conclusion

Cette étude reflète bien la variabilité des résultats lors d'expériences sur le terrain. Contrairement à une étude en canal artificiel, aucun paramètre n'est fixé, et comme chaque paramètre interagit avec d'autres paramètres, il est très difficile de quantifier la part exercée par chacun d'entre eux sur le transport sédimentaire.

Cette étude a tout de même permis de s'assurer que le protocole mis en place par suivi RFID fonctionne correctement, avec des taux de récupération des traceurs satisfaisants. Même si aucune corrélation linéaire ne lie la taille des grains et la distance de transport, il semble exister un seuil de taille après lequel le transport serait moins important. L'influence de la morphologie globale comme les « step-pool » ou « planebed » n'est pas significative mais il serait intéressant tout de même de continuer à suivre ce paramètre afin de collecter davantage de données et ainsi permettre une analyse plus fine. La classe de contrainte a suivi l'hypothèse émise mais seulement pour la première année d'expérience. En effet, la première année la classe sans contrainte avait une plus grande distance de transport pour Sikträskbäcken et Isbergsbäcken. Mais étonnamment, la deuxième année c'est la classe enterrée qui se déplaçait le plus loin.

Cette étude a également permis de constater le grand aléa lié à la présence des blocs rocheux. Cela a également confirmé l'importance de la pente corrélée positivement au transport sédimentaire. De plus, le mouvement empirique des traceurs ne suit pas la prévision obtenue avec le seuil d'entraînement basé sur le Shields critique proposé par Lamb. Cette méthode est donc inadaptée à ce type de rivière semi-alluviale. Des études plus précises pourraient permettre de trouver un seuil critique plus représentatif des interactions avec les blocs dans le lit.

Le fait de ne disposer que de deux ans d'expérience, dont un an n'est pas vraiment représentatif du processus dans des conditions naturelles, limite la portée de l'étude. Cependant, il est important de continuer à surveiller les rivières pour suivre leur évolution à l'avenir.

Sur le plan technique, l'étude a permis de mettre en place un protocole de traitement des données de terrain. Avec notamment, l'écriture de scripts en langage R permettant de réaliser des statistiques sur les données.

7.3 – Pictures of the reaches (from Lina Polvi Sjöberg)



Mattjokkbäcken

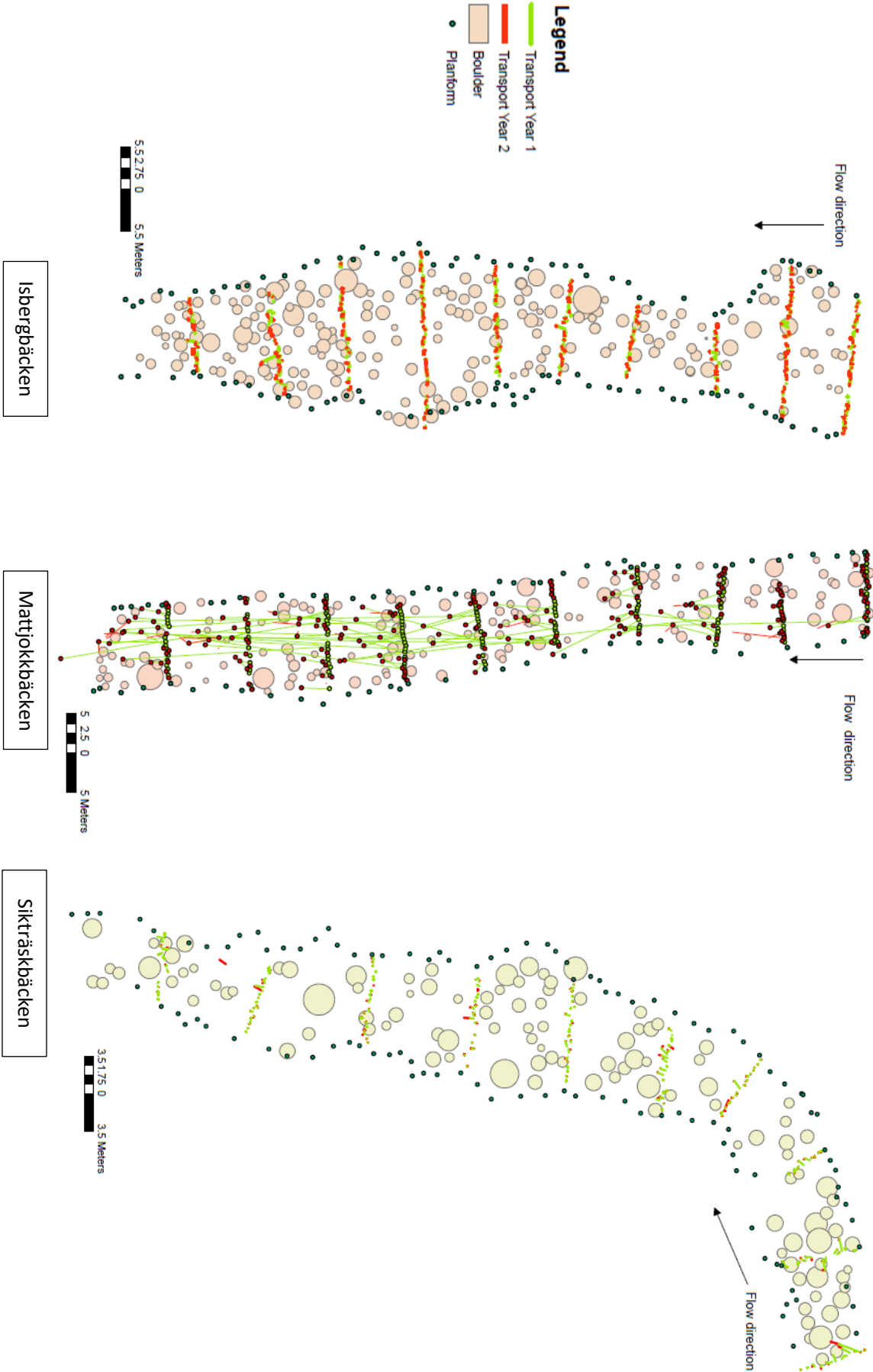


Isbergsbäcken

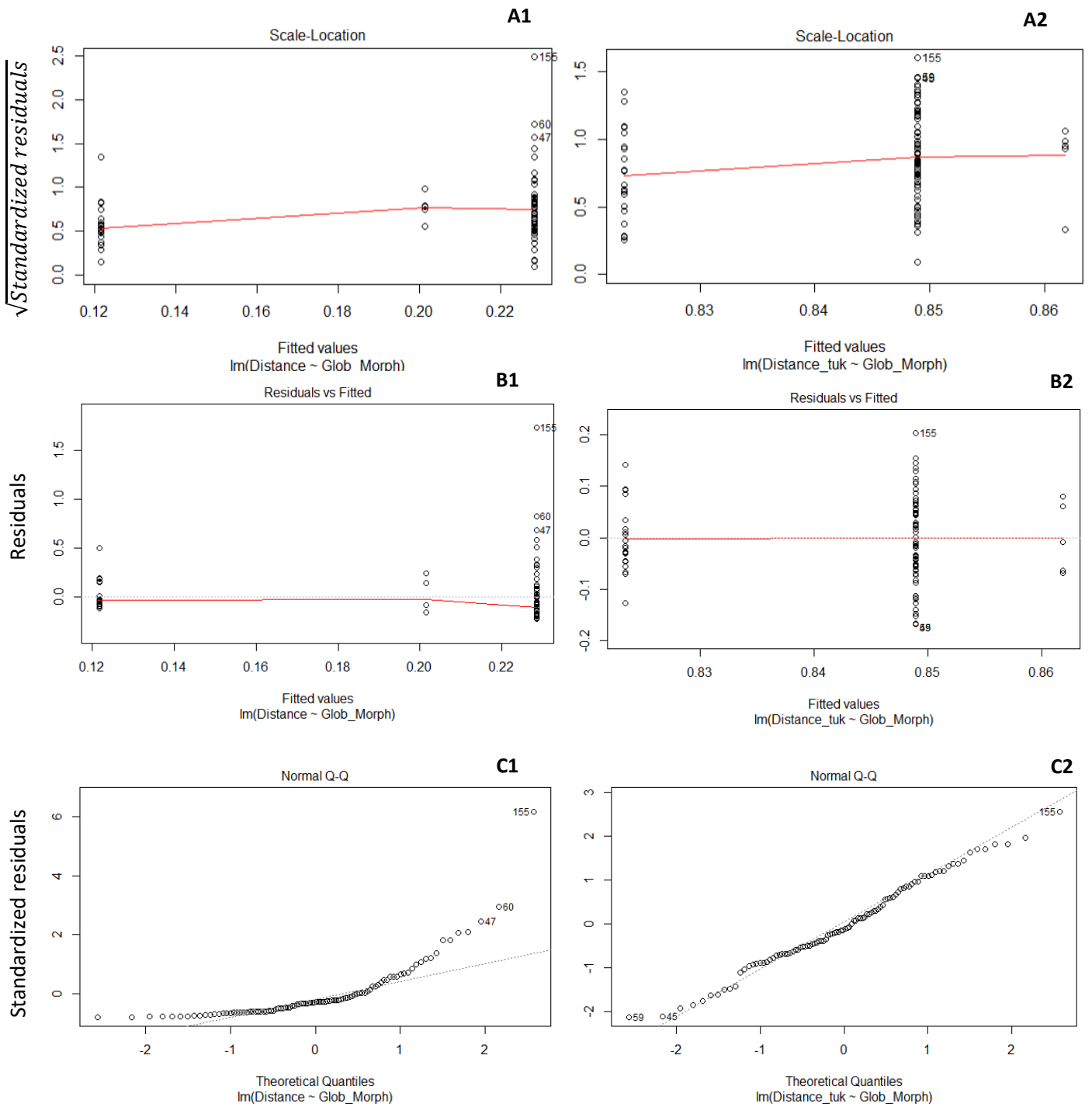


Sikträskbäcken

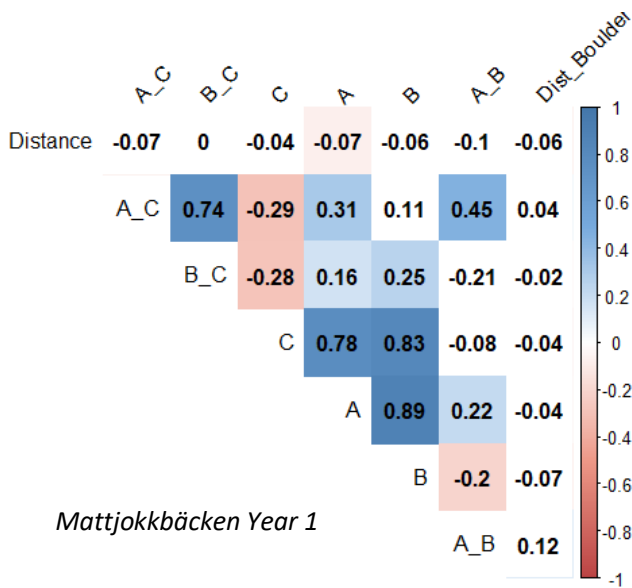
7.4- ArcGIS maps of the reaches: A is Isbergsbäcken, B Mattjokkbäcken, C Sikträskbäcken



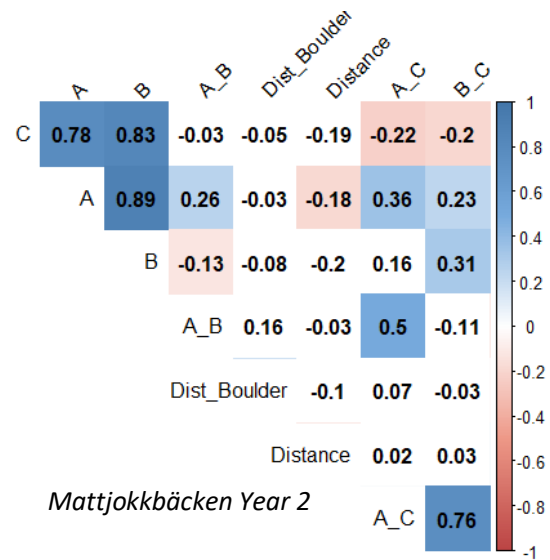
7.5- Assessment of the ANOVA hypothesis; example with in column 1 the tests one untransformed data and in column 2 the results after a Tukey transformation; line 1 represents the variance test with a Barlett test; line 2 represents the Durbin Watson test for independence; line 3 the Shapiro test



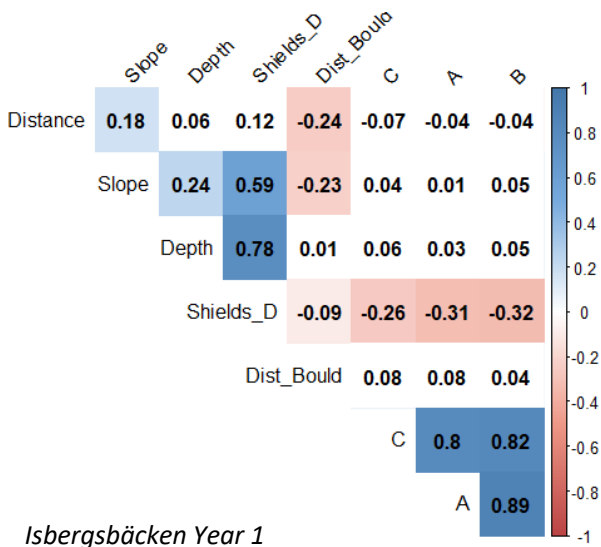
7.6- Spearman correlation matrix, white boxes mean that the correlation is not significant, the intensity of color stands for the degree of correlation. The correlation is indicated inside the boxes.



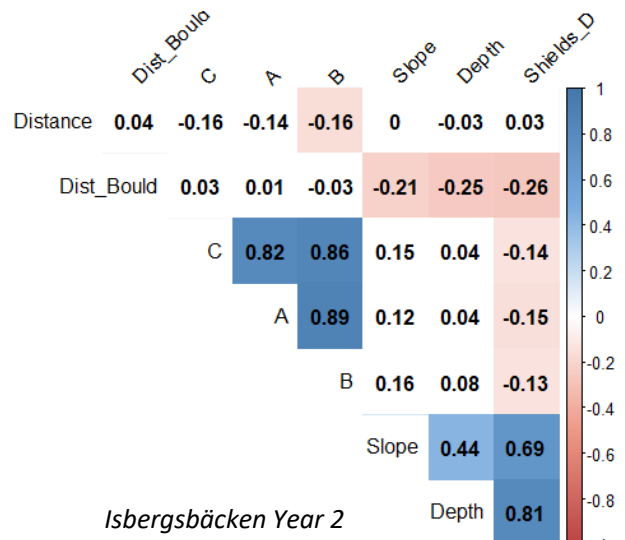
Mattjokkbäcken Year 1



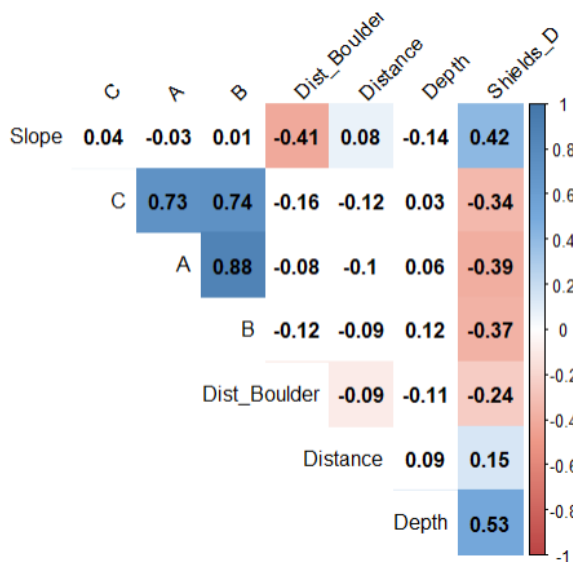
Mattjokkbäcken Year 2



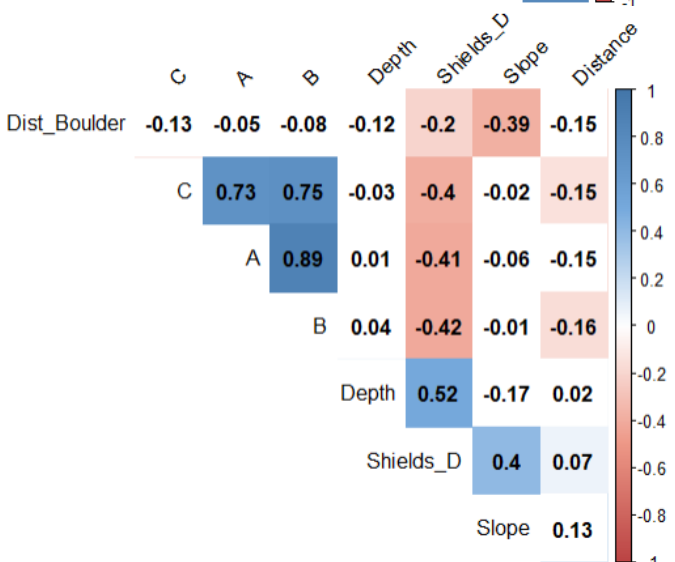
Isbergsbäcken Year 1



Isbergsbäcken Year 2



Sikträskbäcken Year 1



Sikträskbäcken Year 2

MEMOIRE DE FIN D'ETUDES

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Résumé :

This study aims to identify sediment transport controls in semi-alluvial boulder-bed rivers. Tracer movement was collected over a two-year period using passive radio frequency transponders. Each tracer was associated with a class of constraint, morphology and its relative proximity to a rock. This study deals with the data relating to reaches of three different rivers.

No clear pattern was found, showing a high variability associated to hydraulic perturbation related to the boulders in the stream. No grain size correlation with the transport distance was found and it seems like the class of constraint does not control the sediment transport as expected. Furthermore, the forecast of the incipient movement cannot rely on basics critical Shields stress as Shields or Lamb's one.

Mots-clés : River geomorphology, sediment transport, semi-alluvial river, boulders, constraint,