S. Bizzi, M. Tangi, A.Castelletti

Network scale sediment connectivity to explore stability and resilience of channel patterns in the Vjosa basin

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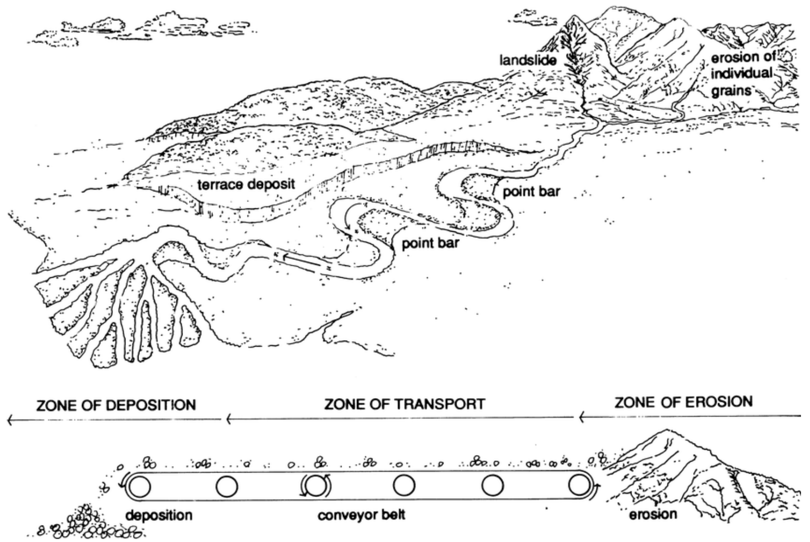
Large scale sediment connectivity assessment

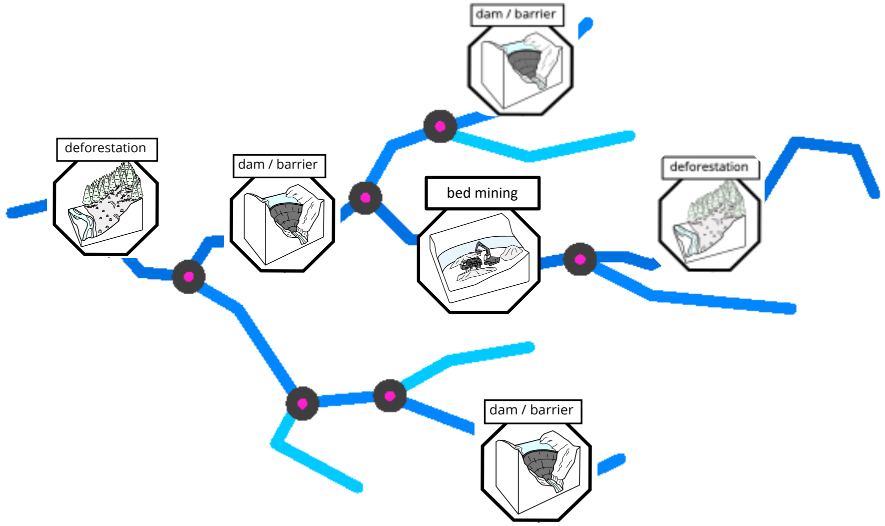
Rivers are **deeply interconnected and complex systems**, where **sediment transport** plays a fundamental role in the process of **fluvial geomorphology, ecosystem integrity, transport of nutrient and erosion:**

- **Quantifying sediment connectivity fluxes is an important, albeit difficult task to achieve,** since it requires a basin-scale perspective, and large amount of data.

- **Multiple alterations** across a single network may have **cumulative** impacts, which are impossible to foresee just with **local impacts assessment**.



From Kondolf, G.M., 1997. Hungry Water: Effects of Dams and Gravel Mining on River Channels.



The CASCADE model – introduction

The **CASCADE model** is a **basin-scale sediment transport modelling framework:**

- It provides **disaggregated information on sediment fluxes and composition** for a single water discharge scenario.
- It has **limited data requirement**, most of which can be obtained **via large scale models or datasets**
- **Used for defining sediment connectivity alteration indicators** for multi-objective decision framework.

RESEARCH ARTICLE | ENVIRONMENTAL STUDIES

Planning dam portfolios for low sediment trapping shows limits for sustainable hydropower in the Mekong

R. J. P. Schmitt[1,2,*], S. Bizzi[3,4], A. Castelletti[3,5], J. J. Opperman[6] and G. M. Kondolf[2,7]

+ See all authors and affiliations

Science Advances 23 Oct 2019:
Vol. 5, no. 10, eaaw2175
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nature sustainability

Article | Published: 09 February 2018

Improved trade-offs of hydropower and sand connectivity by strategic dam planning in the Mekong

R. J. P. Schmitt, S. Bizzi, A. Castelletti & G. M. Kondolf

Tracking multiple sediment cascades at the river network scale identifies controls and emerging patterns of sediment connectivity

Rafael J. P. Schmitt[1], Simone Bizzi[2], and Andrea Castelletti[1,3]

The CASCADE Toolbox – available material

The CASCADE toolbox code and user are freely available at the website **www.cascademodel.org**

Tangi, Marco, et al. "The CASCADE toolbox for analyzing river sediment connectivity and management.»
Environmental Modelling & Software 119 (2019): 400-406.
[DOI: 119. 10.1016/j.envsoft.2019.07.008]


Environmental Modelling and Software 119 (2019) 400–406

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The CASCADE toolbox for analyzing river sediment connectivity and management

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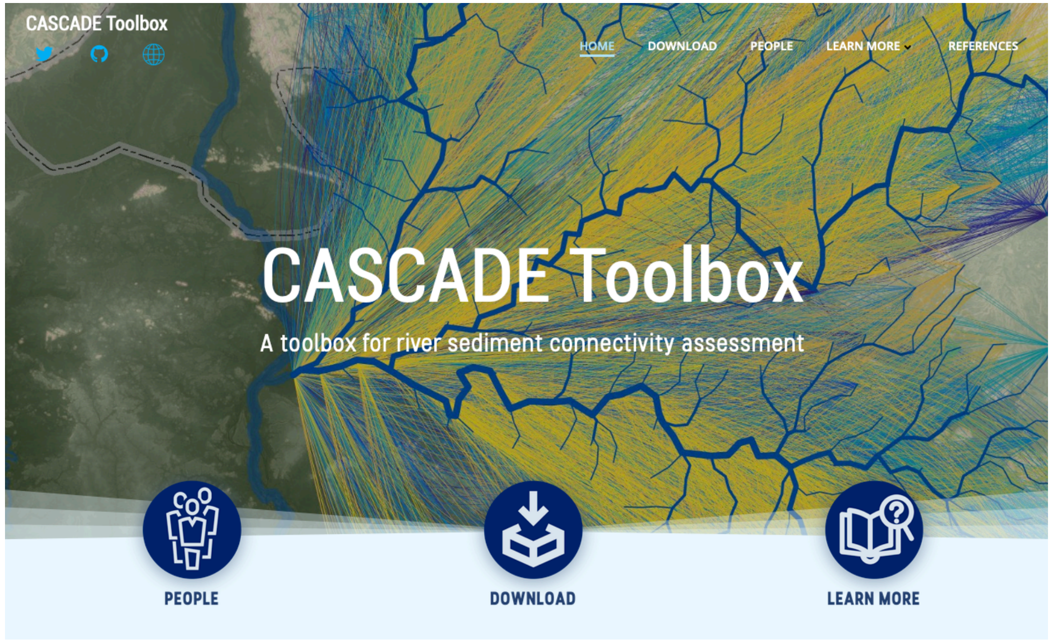
[b] The Natural Capital Project and Woods Institute for the Environment, Stanford University, United States

CASCADE toolbox website
(cascademodel.org)

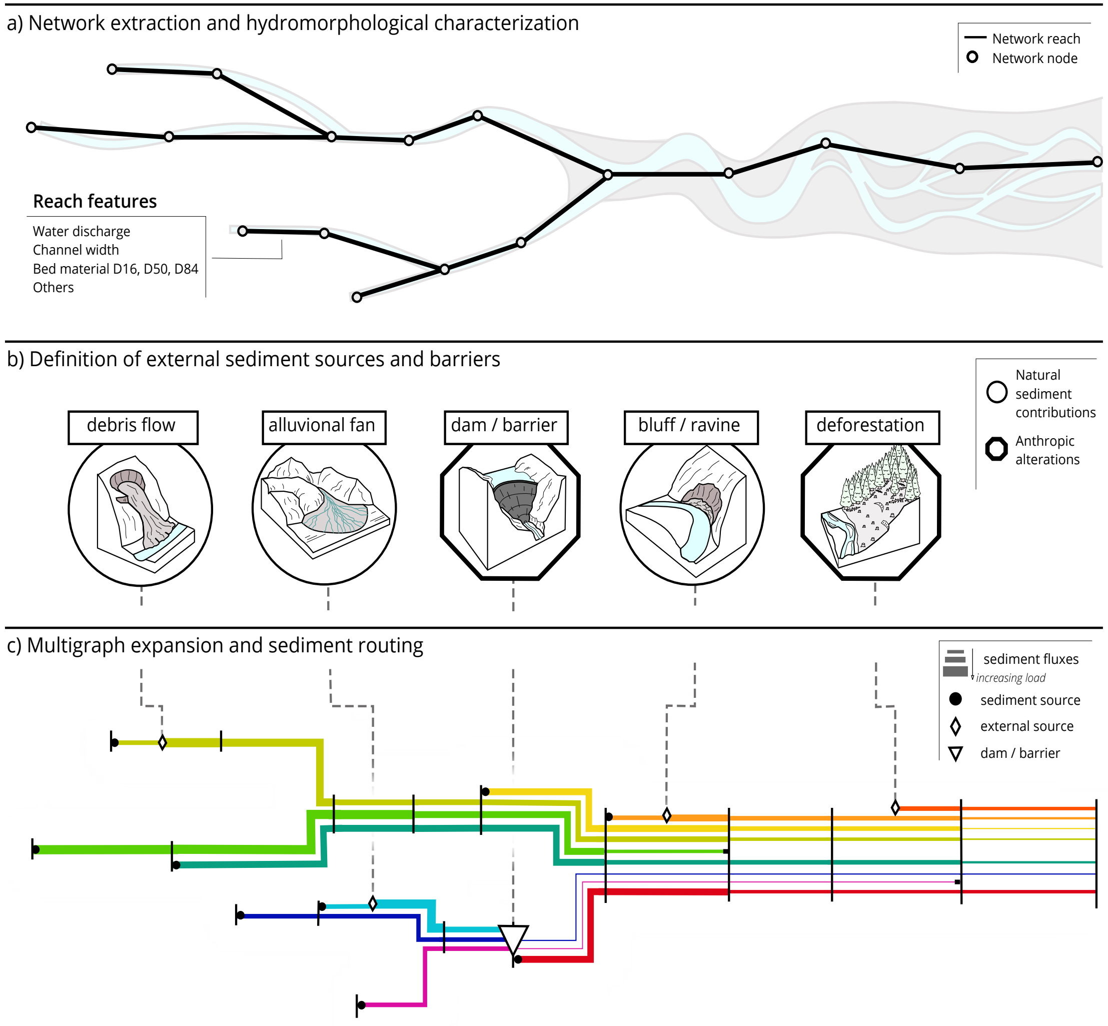


The CASCADE model – basic principles

a) CASCADE first extracts the **river network** and **assigns hydro-morphologic parameters** to each reach.

b) Second, **external sources** are described in terms of sediment supply rates and supplied grain size distribution. **Dams** can also be included by specifying their flooded area and sediment trap efficiency.

c) Third, **the sediment connectivity** is described as a **combination of individual sediment transport processes** called **cascades**, each one with a unique source and downstream path. The **amount of sediment passing** is determined by the **reach transport capacity.**



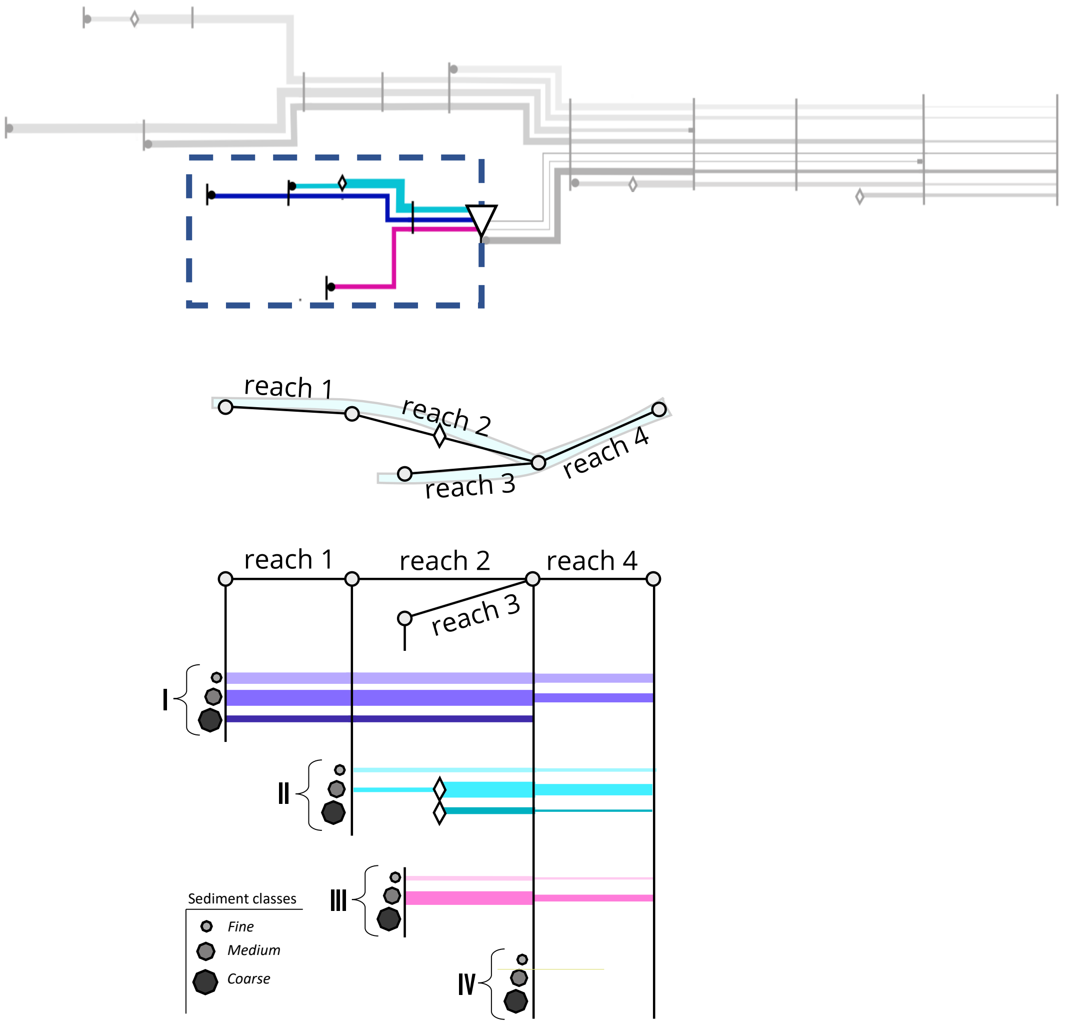
The resulting **outputs** are **information on sediment flux and origins** in each river reach and **information on the fate of sediment** from each source as it travels through the downstream network.

The CASCADE model – basic principles

In the model framework, **cascades are composed by multiple sub-cascades, each transporting sediment of a specific size,** based on user-defined classes**.**

Each sediment source supply a **distribution of multiple grain sizes.**

This framework is useful to **represent** more realistically **processes supplying different grain sizes** classes to the river network, e.g., mass movements might supply both very fine and very coarse sediment fractions at the same location.



Visualization of the sediment routing process

The CASCADE model – basic principles

The CASCADE model provide estimation of instantaneous sediment fluxes for a single discharge scenario. To obtain estimation of **annual sediment flow, the model is run with multiple discharge scenario**.

To compress hydrological informations and save computational time, **only a limited number of scenarios are used**. The values of discharge of the scenarios and their annual frequency can provide a good representations of the whole hydrograph of the network reaches, provided that **the scenarios are in sufficient numbers and covers also rare but high-magnitude events**.

The discharge scenarios are simulated individually in CASCADE, then the resulting instantaneous sediment flows (in Kg/s) are aggregated using the annual frequency of each scenario to obtain the annual sediment flow.

Objectives

The aim of the work is to test CASCADE output ability to predict geomorphological fluxes and features:

Objectives:

1. to validate CASCADE outputs of bed load GSDs and annual sediment flow on the Vjosa case study, while tackling the challenge of model initialization.
2. To evaluate the empirical links between connectivity predicted by CASCADE and channel patterns

The case study – The Vjosa river

The Vjosa river is a unique river in Europe, being one of the last remaining free-flowing fluvial systems in the continent.

This gravel-bed river, with the exception the first 10 km near its source in Greece, flows for the entirety of its 260 km course in Albania **completely untamed**.

Most impressively, almost **all tributaries of the Vjosa are intact** and in pristine conditions too, making this river network an outstanding rarity in Europe.

River in the Balkans display a remarkable variety of different channel types, all of them present in the Vjosa basin. The river forms **gorges** and incises the **terraces** in the upper and middle part, forms **anabranching** and **braiding channel** patters when the valley widens and displays **sinuous and meandering** characteristics towards the mouth.

In total, the river drains an area of 6,700 km^2 and discharges in average 204 m^3/s at its mouth.

The case study – The Vjosa river

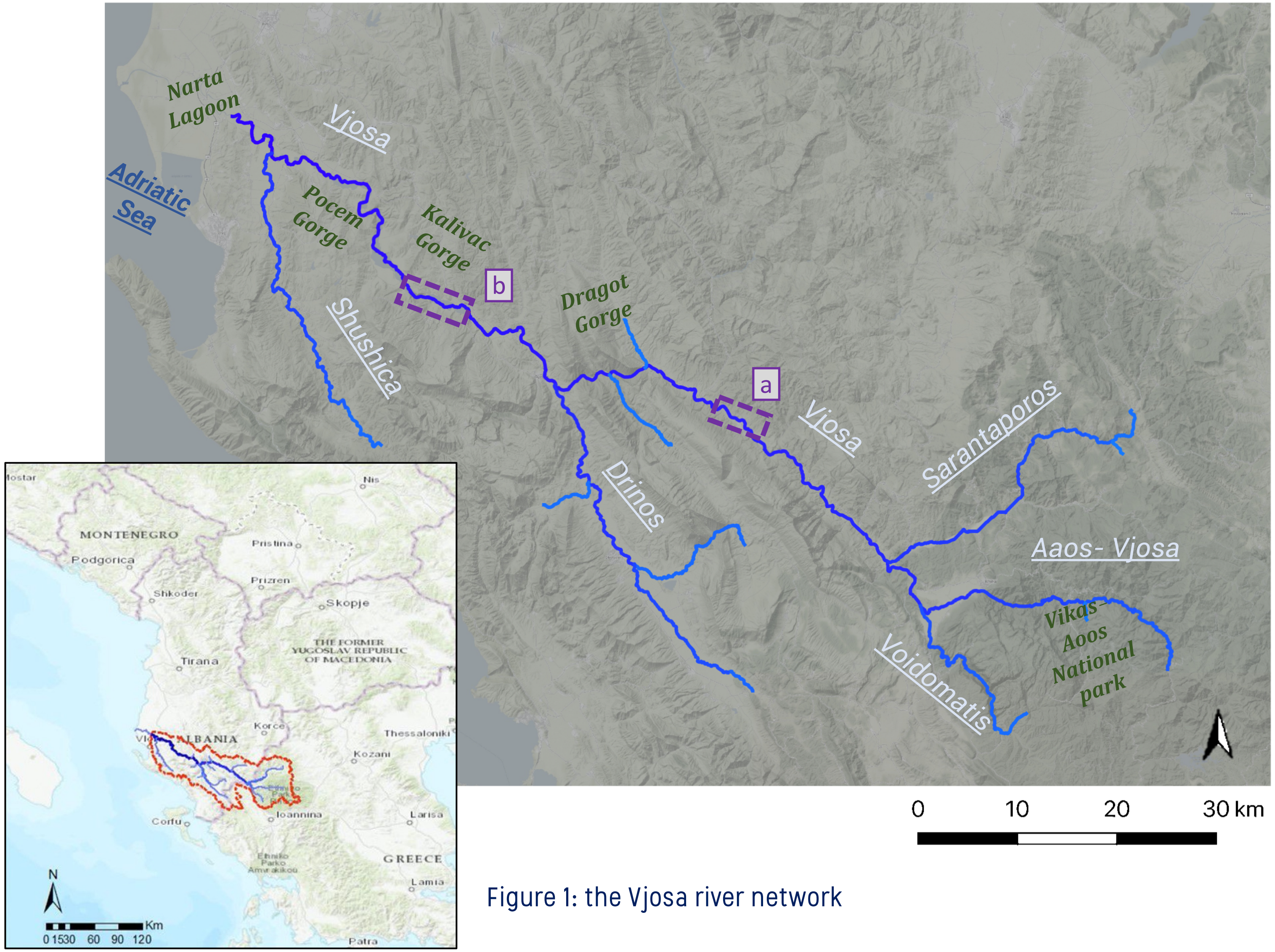
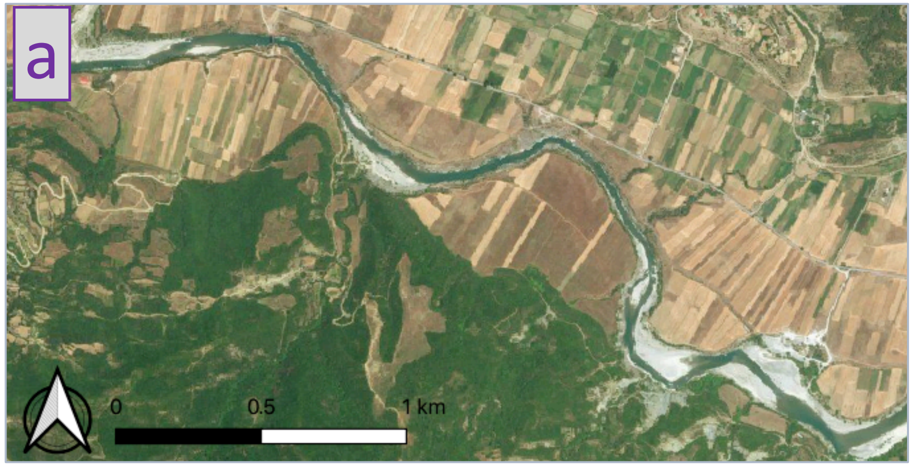


Figure 1: the Vjosa river network

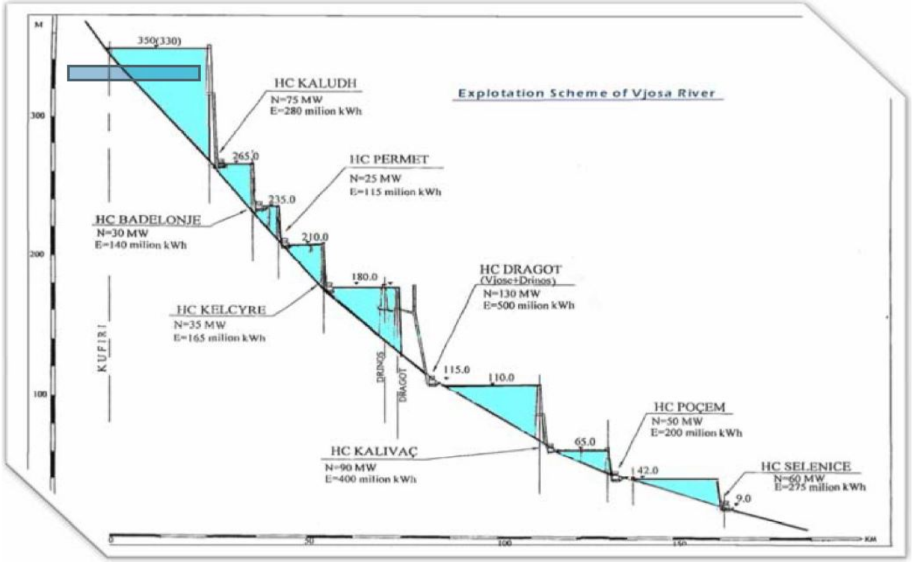


Section confined by terraces in the middle Vjosa (Google images)

Braided section in the lower Vjosa (Google images)

The case study – The Vjosa river

The Vjosa is now involved in a large scale dam development project for hydropower production, which threatens to disrupt the natural river connectivity and damage its unique ecosystems, and cause the disappearance of most of the large and biodiversity-rich braided sections.



Planned dam cascade on the Vjosa main course, data from Sogreah Consultant (2009)

HPPs planned siting and power production, data from Sogreah Consultant (2009)

The case study – The Vjosa river

The scientific knowledge on the Vjosa river system is still very limited, with scarce field data available on the sediment transport, grain size composition and the sediment contribution.

For the validation of this work's results, **we have used 2 sets of data:**

1. **We carried out a field survey in February 2018, collecting grain size data in 6 locations**. Between 5 to 10 pictures were collected in different locations in each site on the main exposed sediment bars (ex in figure 2b) . GSD are calculated using Base Grain software.
2. **Bed load data is recently available at the Pocem bridge in the Vjosa river,** thanks to a recent research initiative **(Hauer et al, 2019).** An adapted version of the **BfG basket sampler** (figure 2c) was adopted to collect base load samples for 4 different discharges, to determine bed load fluxes and composition.

   Based on these, discharge-bed load rating curves were calculated based on linear or power functions. Using the discharges data available at Dorez gauging station, located near Pocem from 1958 to 1990, they derived an **average annual bed load transport of 122.577 Mt/y for the power function** and **47.972 Mt/y for the linear function**.

The case study – The Vjosa river

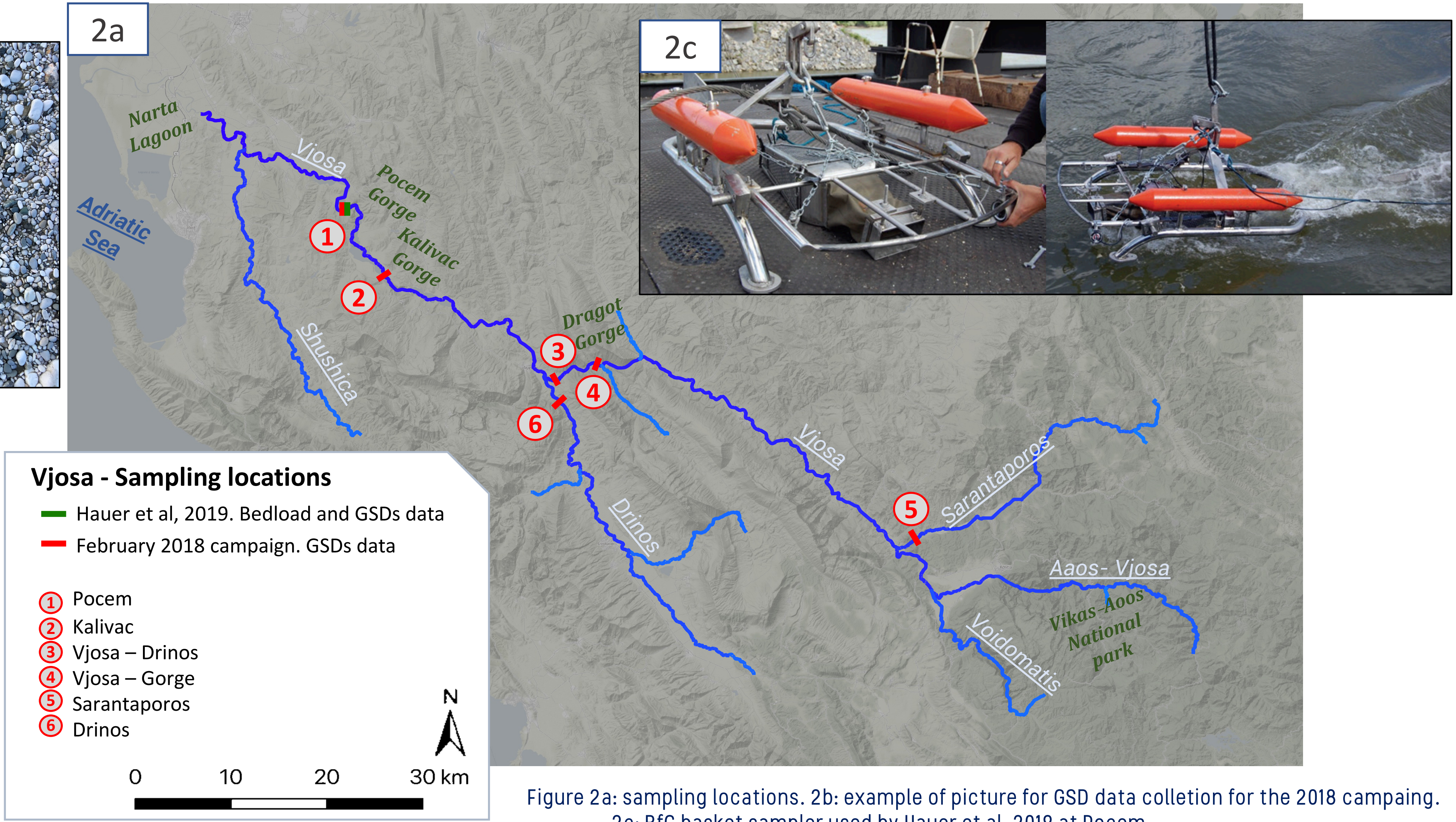


Figure 2a: sampling locations. 2b: example of picture for GSD data colletion for the 2018 campaing.
2c: BfG basket sampler used by Hauer et al, 2019 at Pocem

Input data

- The **network, the slope and the length** of the reaches is extracted from **DEM TANDEM-X** (ground accuracy 10m)
- The **discharge** for each reach from daily data from 1990 to 2004 from **LISFLOOD, a 2D hydrological model.**

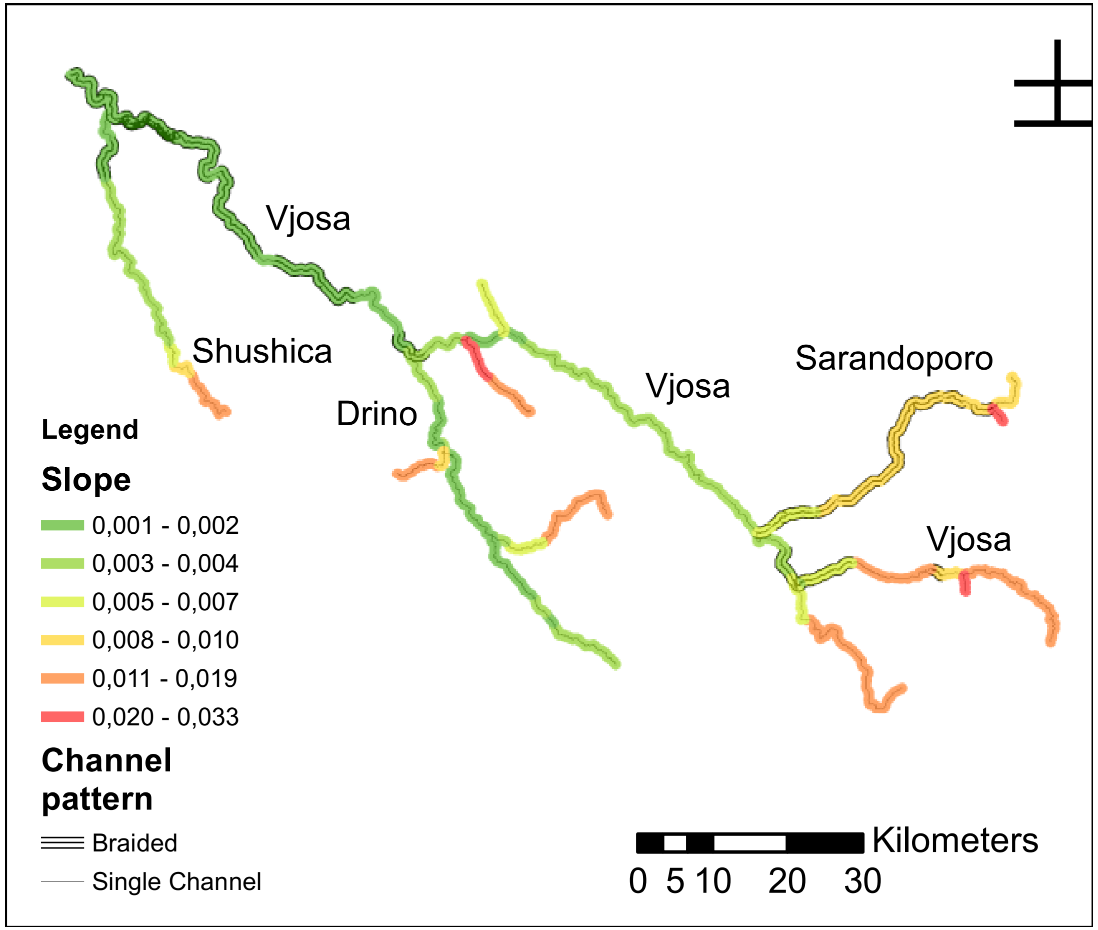
  From these data, we extract **water discharge scenario** to simulate annual transport via multiple CASCADE simulations, as described in slide 7.
- The **reach width and channel type** is obtained from non-vegetated section width measurements from Google images.
- The selective **bedload transport capacity** of the reach is calculated using the **Parker-Klingeman equation** (see supplementary material 1 for more information)

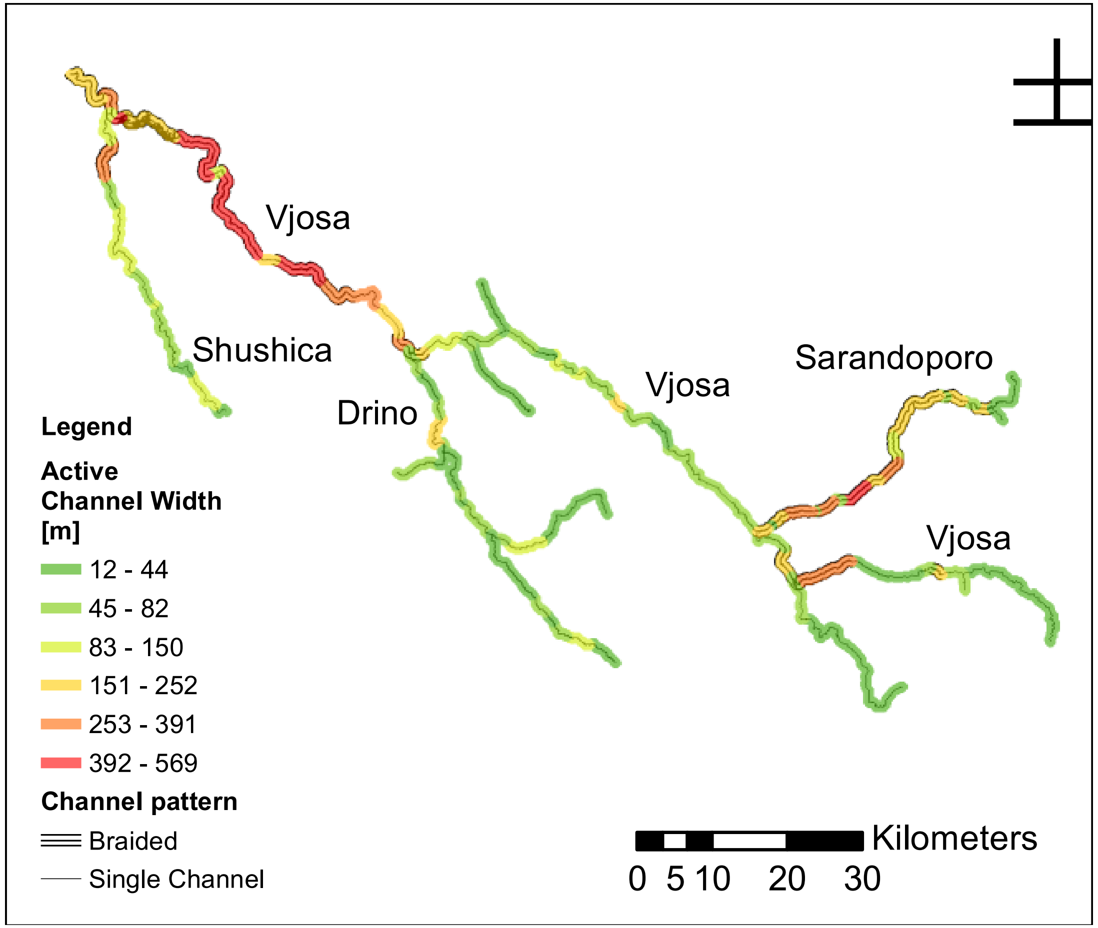
However, **no data is available on reach GSD** except the one used for validation.

Note: Since the data from LISFLOOD are not validated and are likely underestimating the discharge in the network, we are currently looking for other datasets. The results presented here are to be considered preliminary.

Vjosa – Extracted Network

The figure below show the **resulting river network**, the values of **slope** and **width** for all reaches and the classification into single and braided channels.





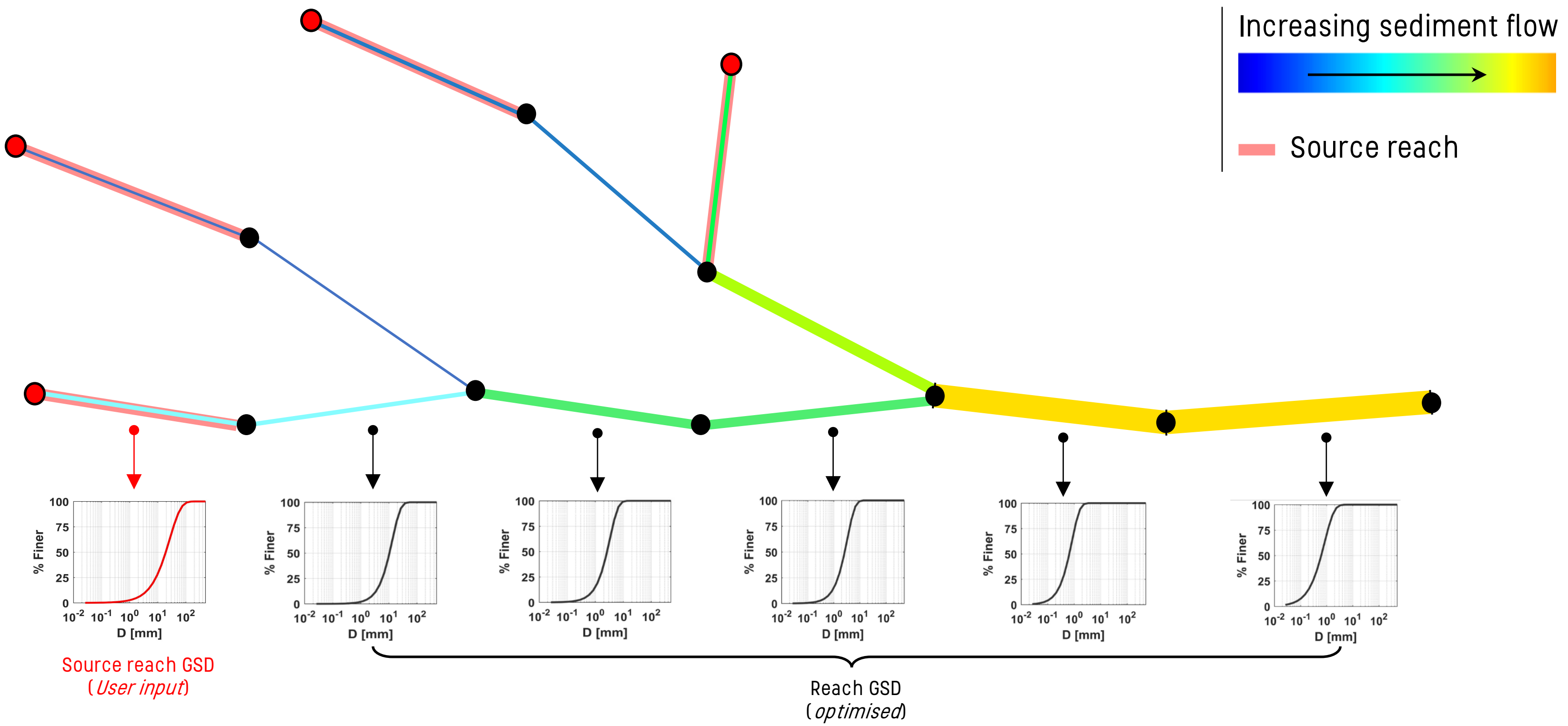
The Ferguson hypothesis for GSD estimation

To obtain reach GSD, we apply the **Ferguson hypothesis** *(Ferguson et al., 2015)* of sediment equilibrium

➢ for each reach: **upcoming sediment flow = sediment transport capacity of the reach**

If in each reach we know the transport capacity, we can derive the GSD necessary to obtain such capacity.

Details on the Ferguson hypothesis and its implementation are available in supplementary material 2



The Ferguson hypothesis for GSD estimation

For the Ferguson hypothesis to work, we need to define the GSDs of the **source reaches, whose initialization is a critical task since it greatly influences the model rounting**

Since no data is available, **we used ranges of GSDs** from **literature** on mountainous, Mediterranean rivers.

The source reaches are divided into **morphotypes** from **satellite images**, and to each one is attributed a range of GSDs.

D50		
Morphotype	Average	Interquartile interval
A	36.68	[27.80 - 40.87]
B	43.76	[33.06 - 52.17]
C	66.37	[44.57 - 79.43]
D	84.35	[63.29 - 100.99]

Table 5.1: *Estimated D50 for the different morphotypes and their associated range of uncertainty.*

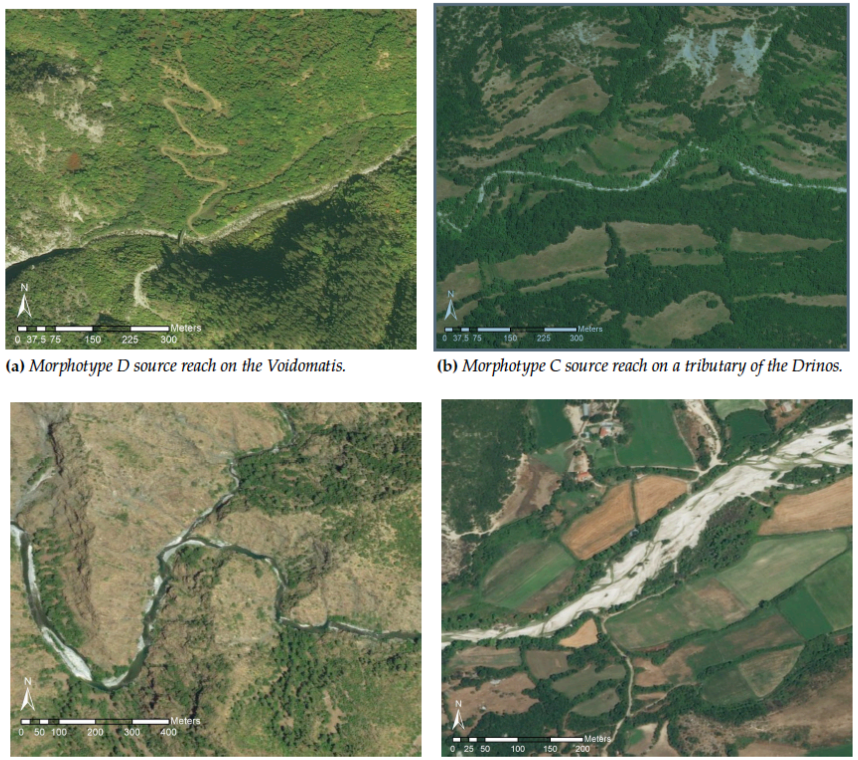
D90		
Morphotype	Average	Interquartile interval
A	94.83	[63.12 - 117.05]
B	125.5	[103.16 - 146.49]
C	206.65	[135.15 - 256.00]
D	264.37	[187.67 - 298.68]

Table 5.2: *Estimated D90 for the different morphotypes and their associated range of uncertainty.*

D10		
Morphotype	Average	Interquartile interval
A	14.83	[11.96 - 17.00]
B	15.2	[11.74 - 18.21]
C	24.08	[14.69 - 32.11]
D	25.41	[18.22 - 33.71]

Table 5.3: *Estimated D10 for the different morphotypes and their associated range of uncertainty.*

Data from Liébault (2003)



(a) *Morphotype D source reach on the Voidomatis.* **(b)** *Morphotype C source reach on a tributary of the Drinos.* **(c)** *Morphotype B source reach, on the Vjosa-Aaos, near the river spring.* **(d)** *Morphotype A source reach, on a tributary of the Shushica.*

Example of the 4 different morphotypes in the Vjosa river network (Google images)

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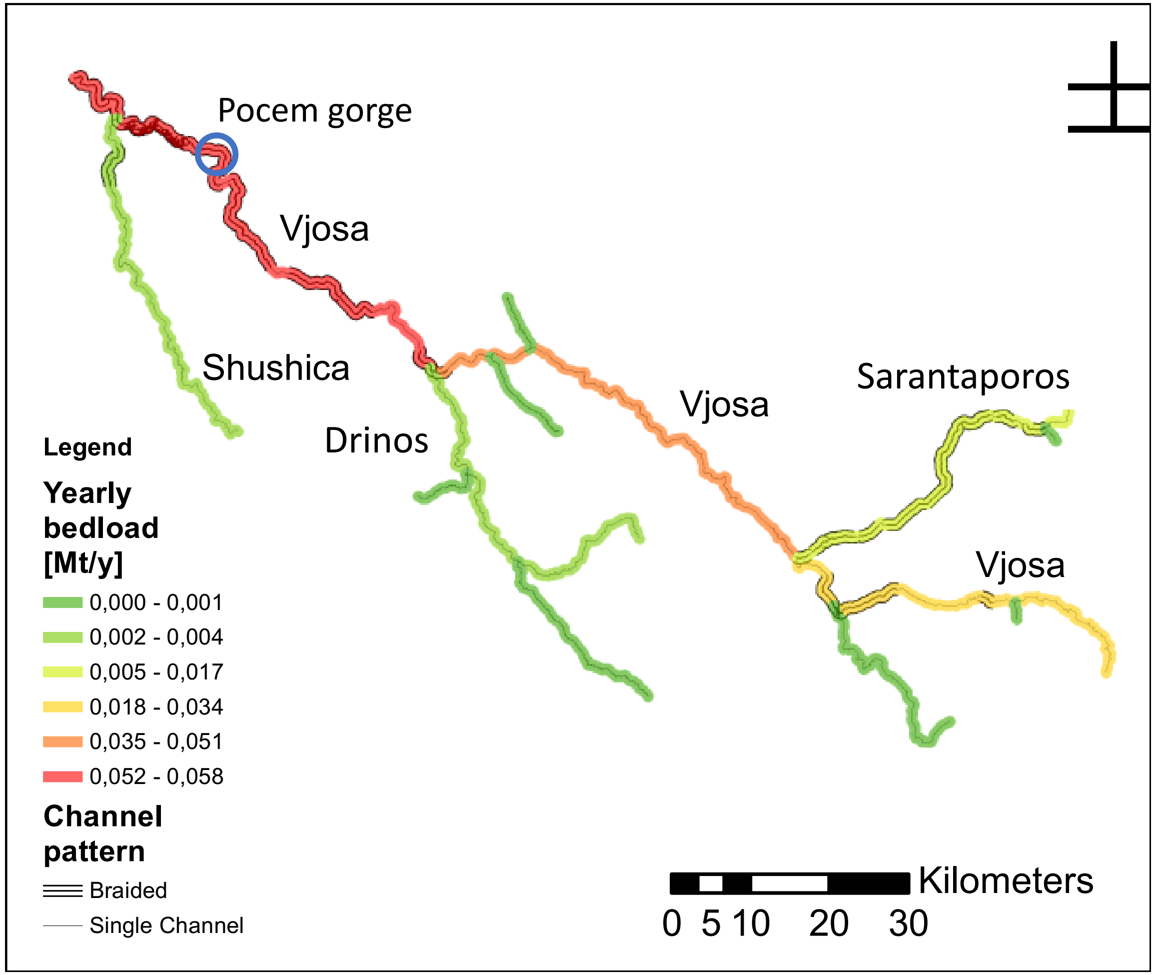
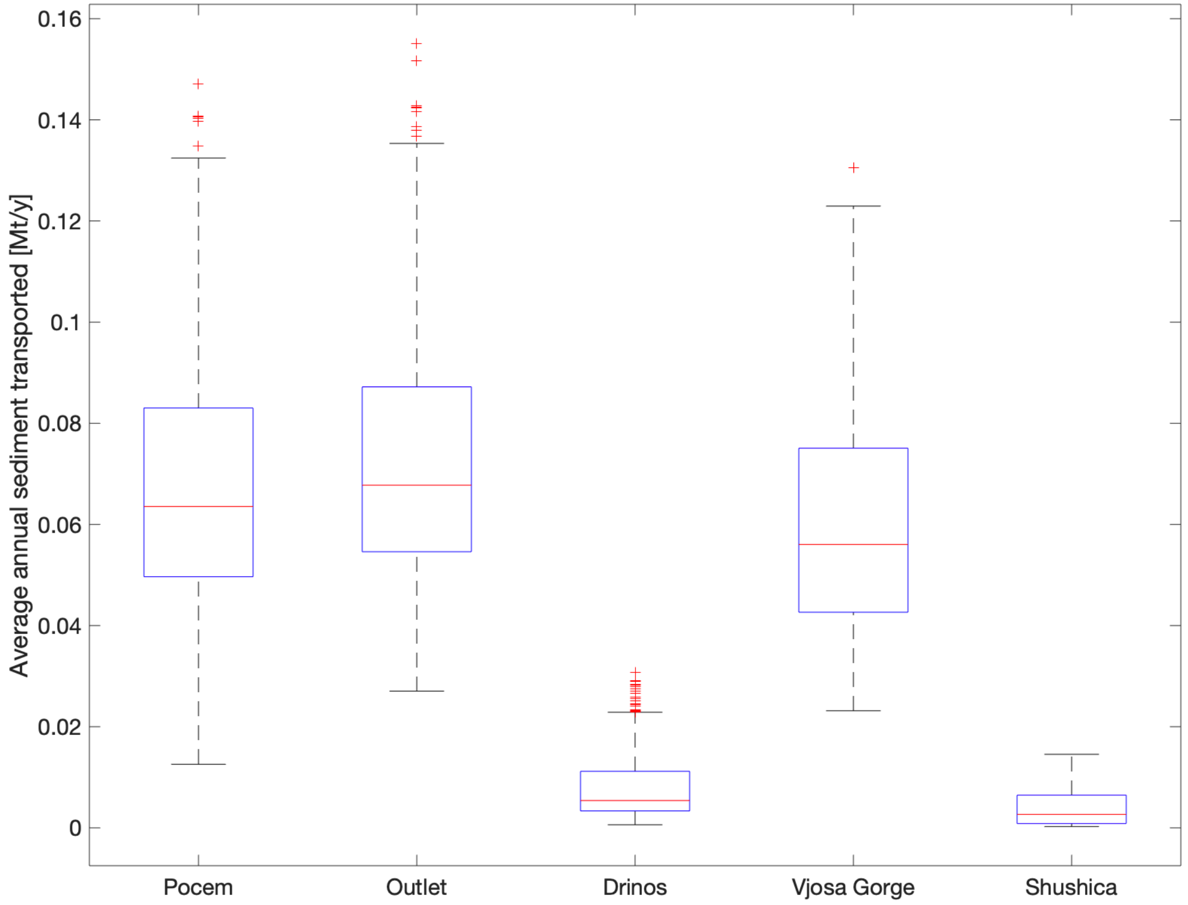
Results – Yearly Bedload

Montecarlo simulation for **1200 different sources reaches GSD initialization** – identified using **Sobol sampling procedure**



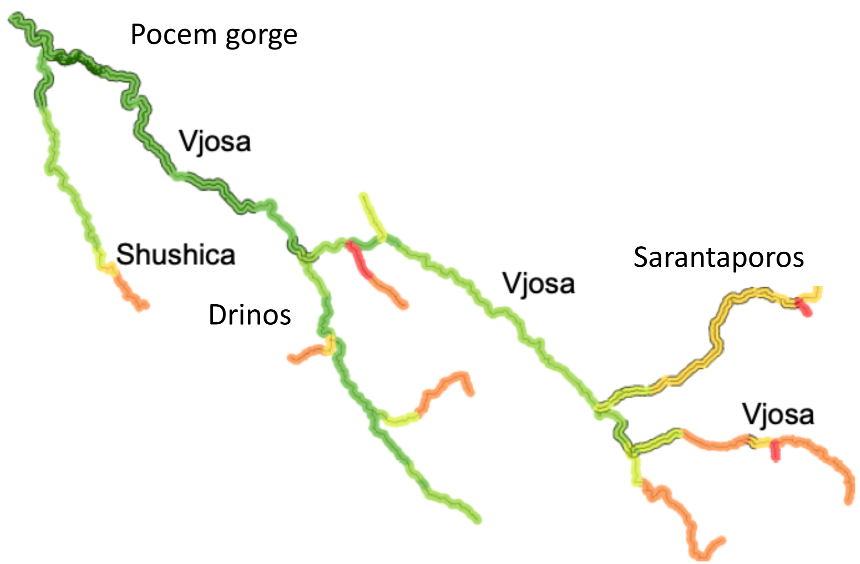
Annual bedload simulated using average sources GSD

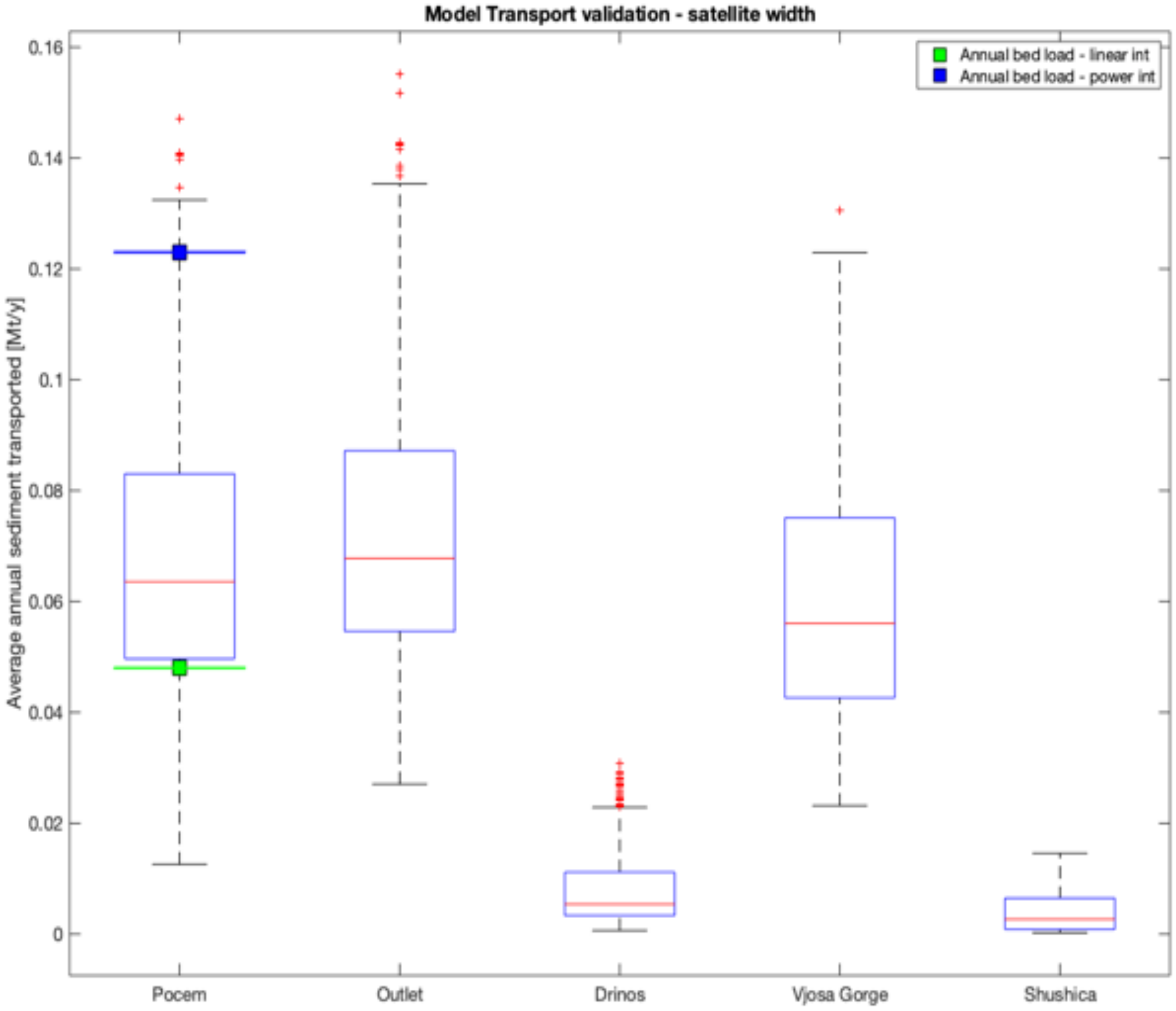


Ranges of average annual sediment transported generated by the set of CASCADE simulations at different locations.

Results – Yearly Bedload

We can validate the ranges of annual sediment transport from the **Montecarlo simulation** with the **field data from Hauer et al. (Boku) survey,** extrapolated with **linear and power interpolation** to extract **average annual sed. flux.**



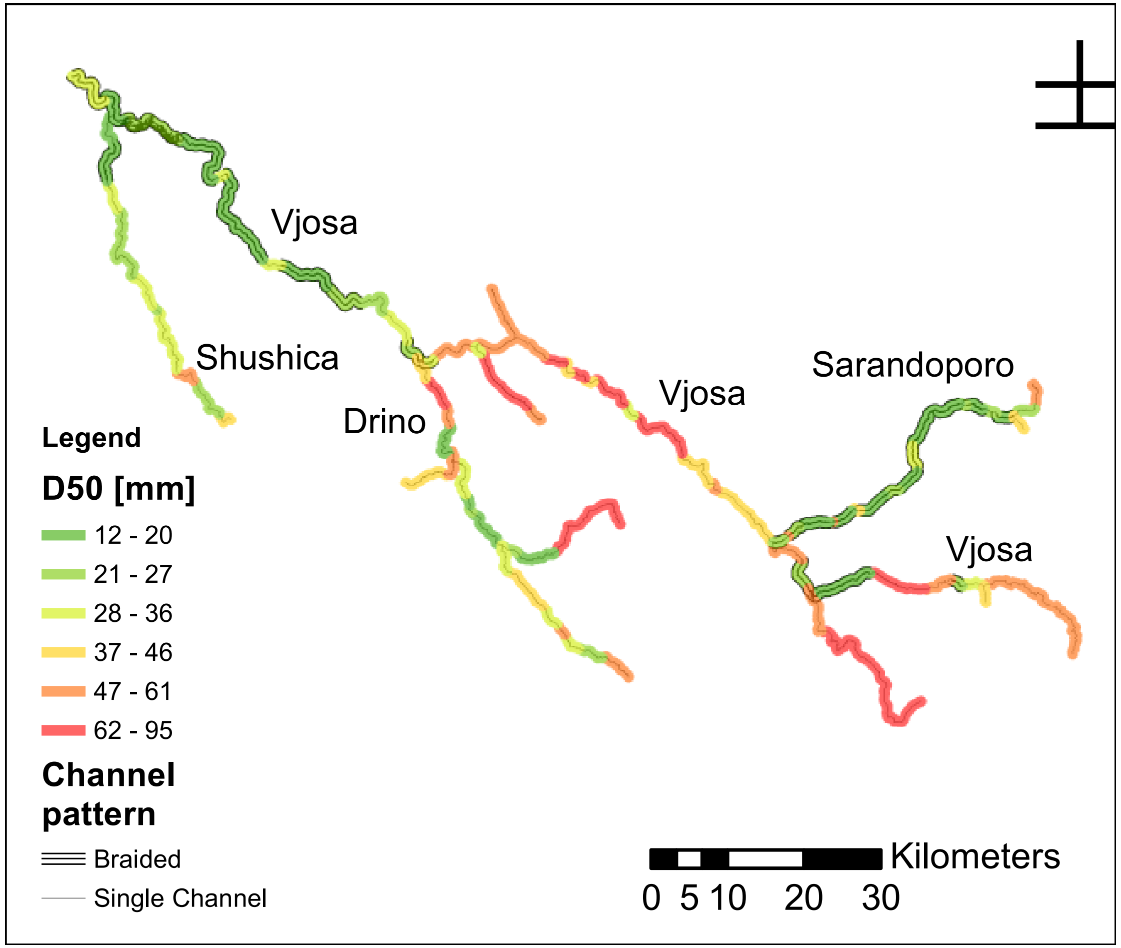


Ranges of average annual sediment transported generated by the set of CASCADE simulations at different locations .

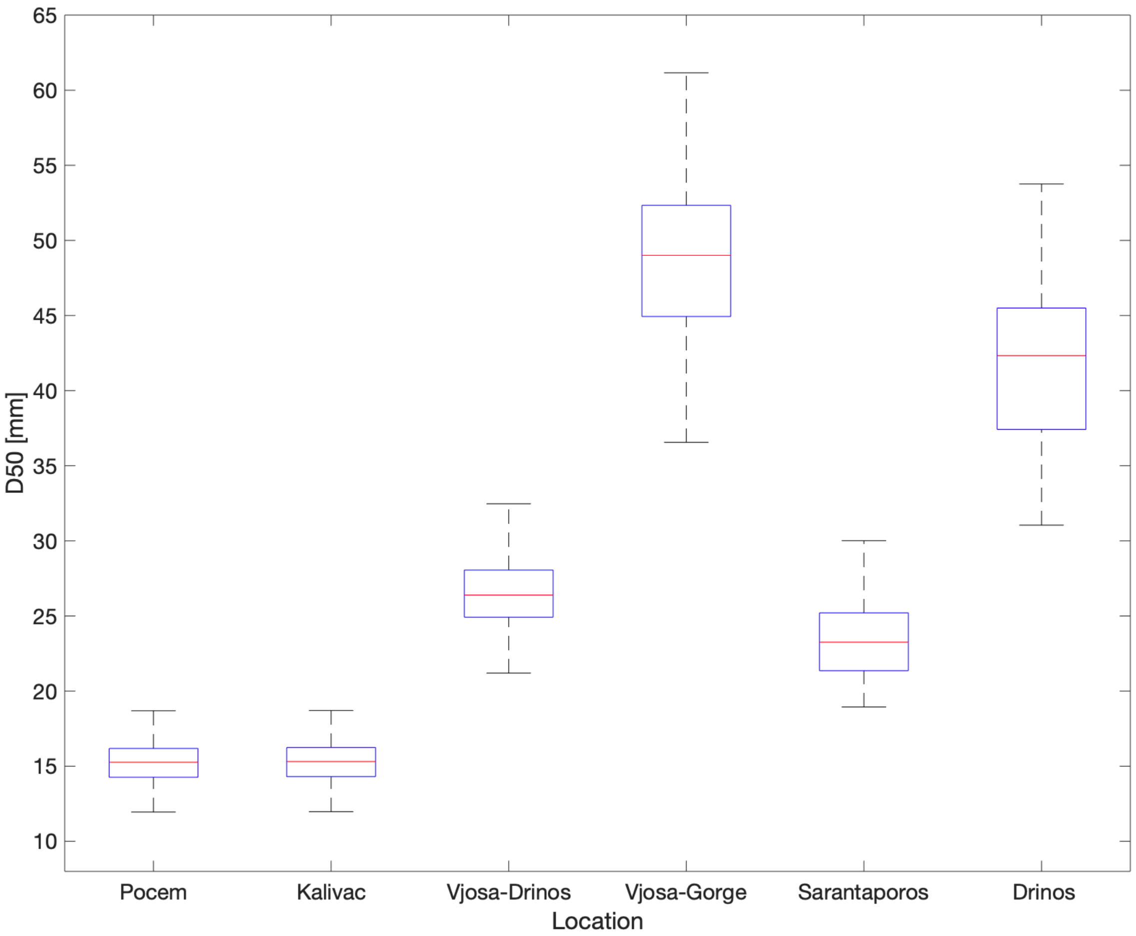
The two lines in Pocem reports the values obtained for linear and power functions applied to sampled bedload data (Hauer et al 2019).

Results – GSD

Montecarlo simulation for **1200 different sources reaches GSD initialization** – identified using **Sobol sampling procedure**



Reach D50 obtained using average sources GSD



Ranges of D50 values from the sensitivity analysis of the sources GSD

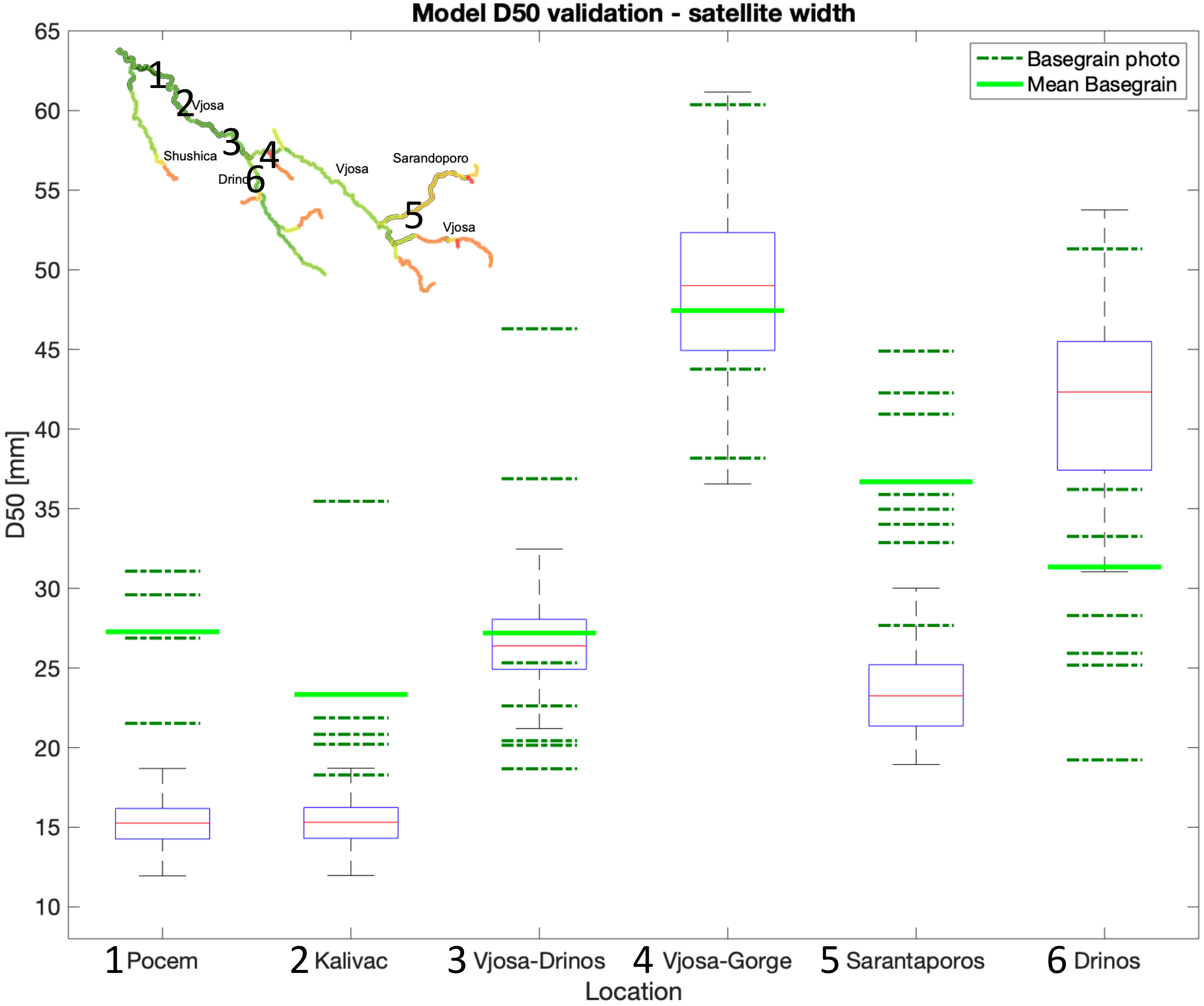
Results – GSD

We can validate the results using the **GSDs from ground photos** collected in the field survey

The bed load GSDs found by CASCADE is slightly finer then the ground GSDs, fact also reported by the **Hauer et al. (Boku) survey**

	date	D10	D50	D90
Bed Load GSD	'15/3/2018'	6	27.7	72.5
	'16/3/2018'	5.6	15	36.3
	'27/3/2028'	5.4	18.7	53.1
	'28/3/2018'	4.2	17.6	50.5
Ground GSD		**14.5**	**27.7**	**65.1**

Bedload and ground GSD collected by the Hauer et al survey in Pocem



Ranges of D50 values from the sensitivity analysis of the sources GSD, compared with the D50 obtained by the February 2018 data campaign (in green)

Comments on the results

Annual sediment fluxes

As seen in slide 19, the range of simulated average annual bed load fluxes is really in good agreement with the two extremes generated by interpolating sampled data.

Being Pocem situated towards the basin outlet and given the good agreement for GSD patterns across the network, we are satisfied by the model validation.

Reach Grain Size Distribution

The fining pattern from Drinos and Sarantaporos to Pocem and Kalivaç is well represented by the CASCADE simulations, as seen in slide 20. In general, **there is a good agreement between sampled data and model outputs** (slide 21).

Often the modelled GSD is slightly finer than the sampled ones. This is in accordance with field data acquired by Hauer et al (2019), where the surficial GSD derived by drone-derived pictures of the site (orange row in the table in slide 21) was always more coarse than the GSD sampled by the BfG basket. This also in accordance with theory where the transported sediment size distribution is expected to be finer than the surficial grain size distribution (probably more in agreement with a volumetric sample, not available in this study).

Braided threshold definition

As the validation have yielded satisfactory results, we now want to test if information on sediment transport and connectivity given by the CASCADE model can help us enrich our understanding of channel composition and patters on the river.

We focused on the definition of **a threshold between single and braided channel using CASCADE outputs**, in order to evaluate the **resilience of the braided section of the river to channel type shifts**, brought by sediment starvation due to sediment trapping in dams.

Historically, braided-single channel threshold formulas (like Eaton et al. (2010)) used slope as a proxy of the sediment concentration and bedload GSD, since these data were rarely available for the whole basin. CASCADE, however, can provide these data.

The threshold formula employed is by Mueller & Pitlick (2014), which uses **bedload concentration and dimensionless bankfull discharge to define the threshold**.

To test the braided thresholds (Figure 5) we will refer only to the outputs of the CASCADE simulation with **source reaches initialized with the average D50 value of each morphotype**.

Braided threshold definition

Mueller– Pitlick threshold (2014)

$$\frac{w}{h} = 425Q^{*0.12}C'^{-2.30}\mu'^{-2.9} \qquad \text{given } \frac{w}{h} = 50$$

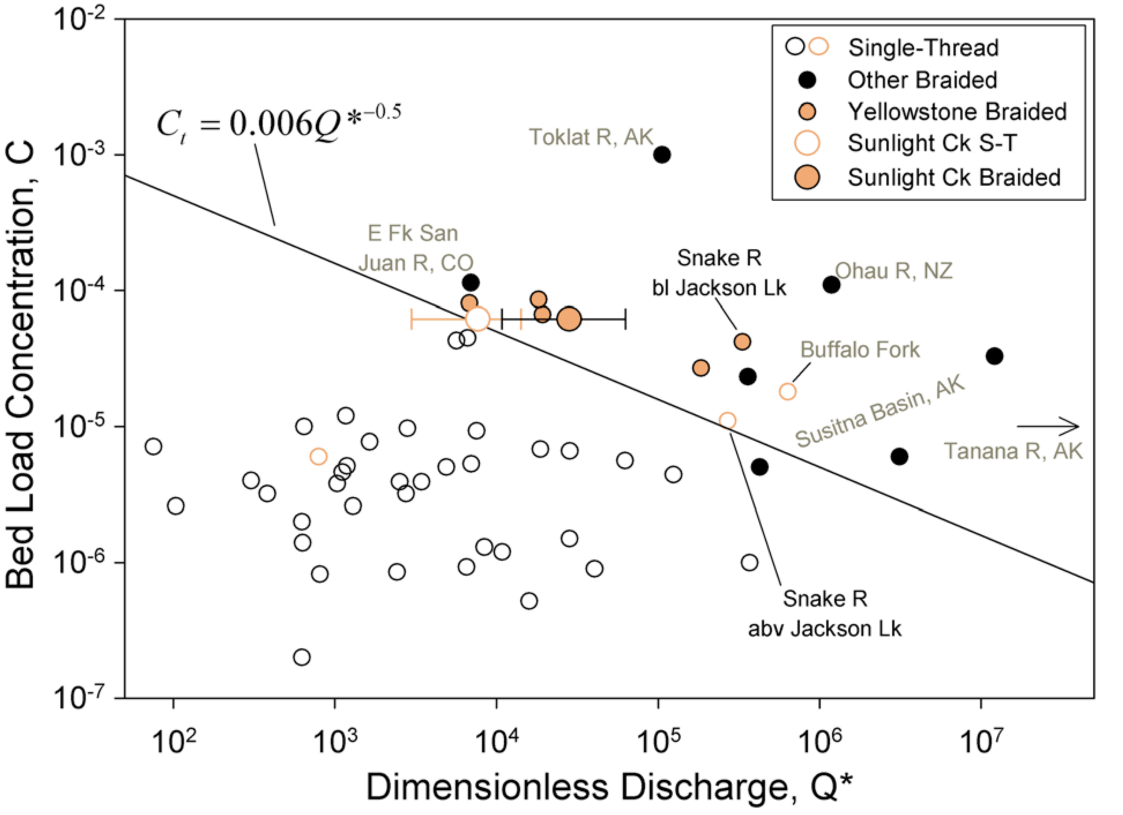
$$\boldsymbol{C = 10^{\left(-2.54Q^{*0.052}\mu'^{-1.26}\right)}}$$

Where:

$Q^* = \dfrac{Q_{bf}}{\sqrt{(s-1)gD_{50}}\,D_{50}^2}$ Q^*= dimensionless bankfull discharge

μ' = bank erodibility [1 – 1.4]

$C' = -log_{10}C$ C = bedload concentration (bankfull Q)



Mueller – Pitlick threshold for the Sunlight Creek basin (from Mueller et al, 2014)

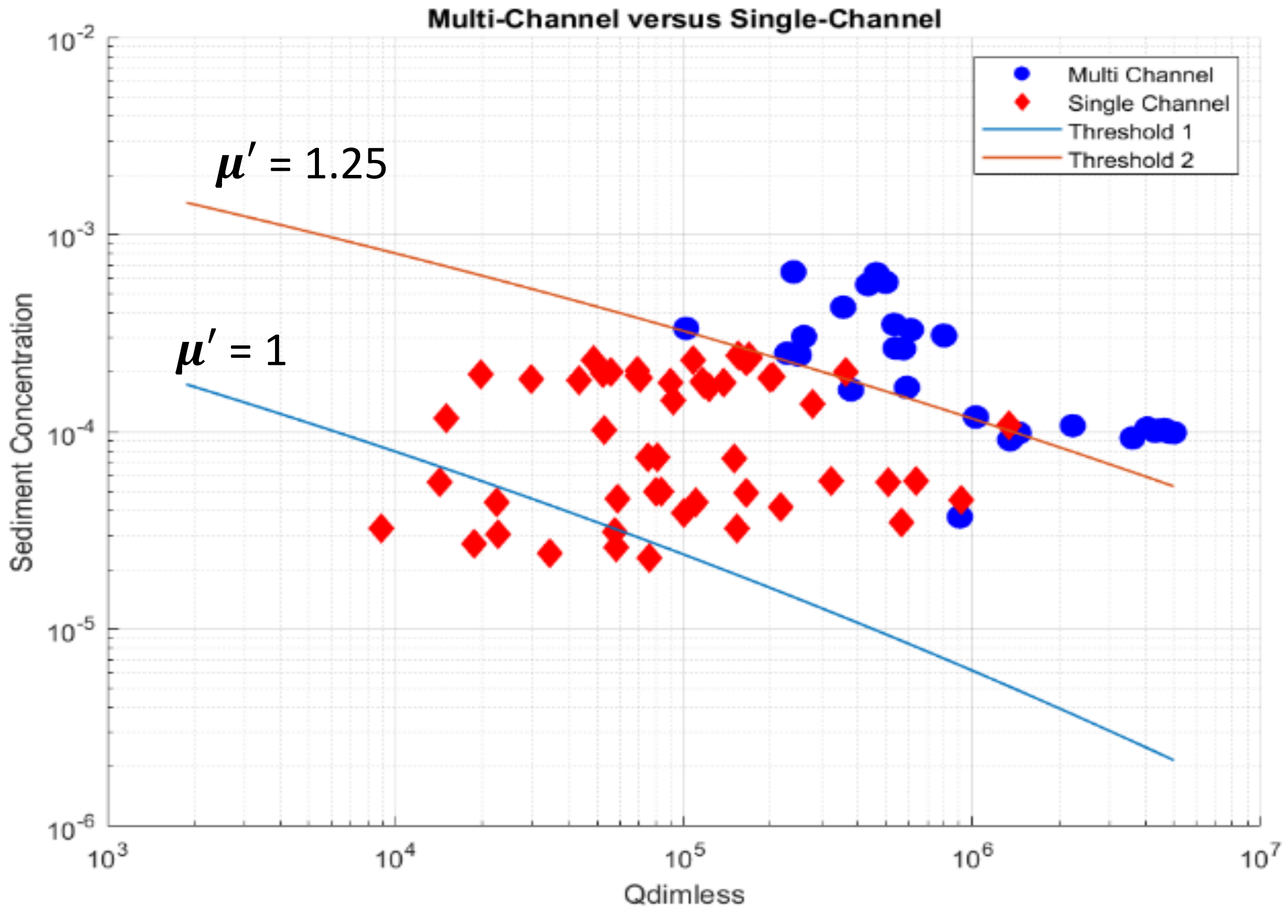
$\boldsymbol{\mu}$‘ is a bank erodibility parameter, ranging from 1 if there is no bank stabilizing effects, to 1.4, if the bank is very resistant to erosion.

Setting μ‘= 1.25 allow the threshold to clearly separate the braided section from the single channel one (figure next slide)

Braided threshold definition

We apply Mueller– Pitlick threshold on the Vjosa

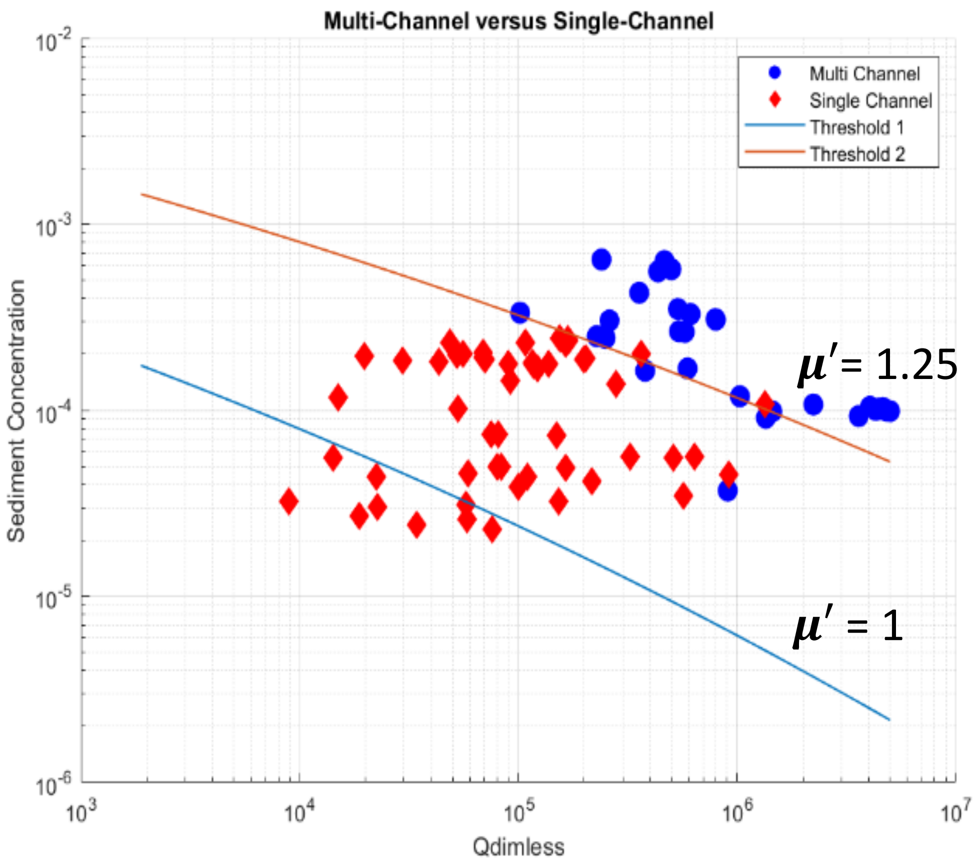
- First, the reaches are **classified into braided or single channel**
- We then run CASCADE for the bankfull discharge scenario, to obtain sediment concentration
- **The D50 is derived from the annual simulation**

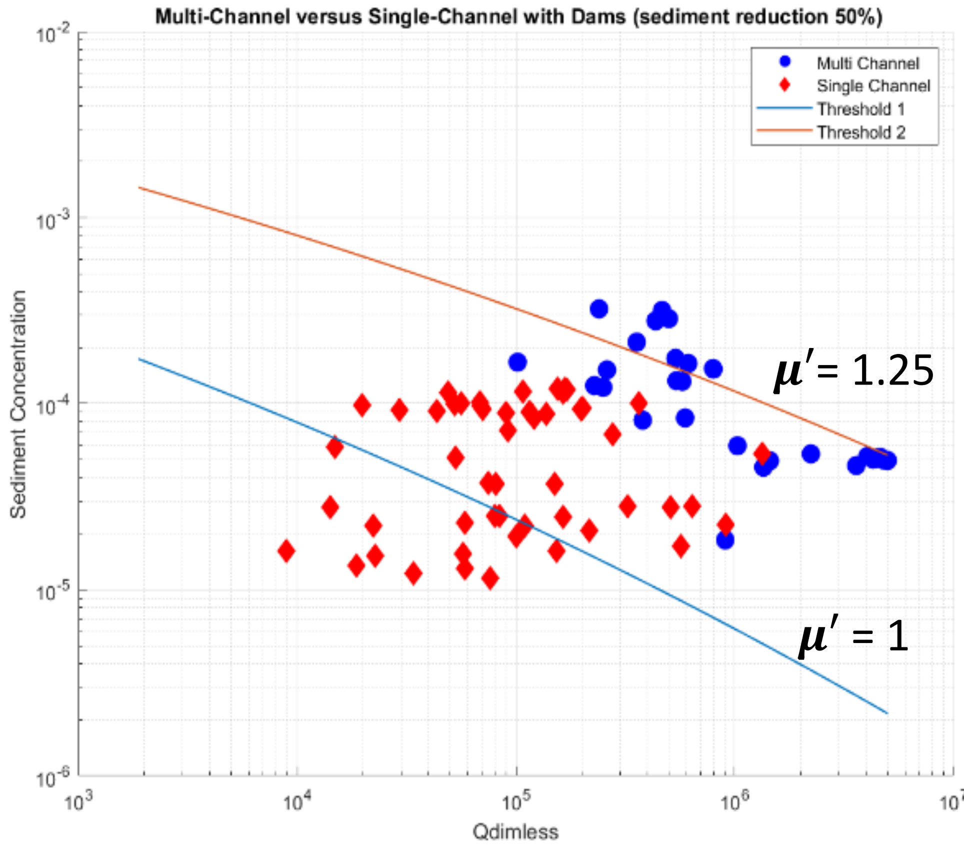


From the figure, we can notice that **many braided reaches are close to the tipping point,** indicating a fragile equilibrium

Braided threshold definition – impact of sediment reduction

We hypothesizing a decreased sediment supply of the 50% for each reach due to dam trapping. From the figure, it is worth noticing that many braided section will pass the tipping points, including the downstream braided reaches (higher values of Q*) which are renowned hotspots of biodiversity.





Conclusion

1. For the first time, we applied the new CASCADE model with a distributed GSDs input, addressing both initialization and validation in a data scarce environment.

2. We integrated **CASCADE simulation output** with more **traditional river geomorphic analysis**, increasing out understanding of the system:
   - We successfully identify a viable **braided threshold** for the reaches of the Vjosa;
   - We assess the **resilience to channel type shift** caused by sediment fluxes depletion.

Future developments

The results presented here are preliminary, and many uncertain aspect still need to be addressed:

- The **discharge data obtained by LISFLOOD are most likely an underestimation of the real vakues**, we are currently working on using data from a gauging station near Pocem (the same used by Hauer et al. in their report) to correct the data.

- **The model assumes that the width of the channel is always constant**, while in reality the active channel width changes according to the discharge and the morphology of the river section. This variation is especially pronounced in braided sections. **We are currently working on implementing formulas connecting active channel width with discharge in CASCADE**.

- **An additional sensitivity analysis is being currently performed on the hiding factor γ of the Parker-Klingemann equation** (see supplementary material 1), as the formula is quite sensible to changes in the parameter (now set to $\gamma = 0.05$).

Credits and contacts

Contacts:

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CASCADE toolbox and user manual available at:

www.cascademodel.org

Environmental Intelligence website:

www.ei.deib.polimi.it/

Many thanks to:

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Prof. Andrea Castelletti (Polimi)

And the team at Environmental Intelligence for their invaluable help in this research

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CASCADE model:

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Transport capacity equation:

- Parker, G., & Klingeman, P. C. (1982). On why gravel bed streams are paved. *Water Resources Research*, *18*(5), 1409-1423. https://doi.org/10.1029/WR018i005p01409

Single channel – multi channel threshold:

- Mueller, E. R., & Pitlick, J. (2014). Sediment supply and channel morphology in mountain river systems: 2. Single thread to braided transitions. *Journal of Geophysical Research: Earth Surface*, *119*(7), 1516-1541. https://doi.org/10.1002/2013JF003045

Supplementary material 1: The Parker–Klingemann equation

Parker & Klingemann (1982) equation

$\mathbf{Q_c}$ = Transport capacity for sediment class c [Kg s^{-1}]

$$Q_c = \mathbf{B}\ W_c^*\ \mathbf{F_c}\ \rho_s \left(\frac{\tau}{\rho}\right)^{3/2} (R * g)^{-1}$$

$\mathbf{W_c^*}$ = Dimensionless transport rate for sediment class c [-]

$$W_c^* = 11.2 * \left(1 - 0.853 * \frac{\tau_{rc}}{\tau}\right)^{4.5}$$

τ = bed shear stress [Kg m^{-1} s^{-1}]

$$\tau = \rho\, g\, \mathbf{H}\, \mathbf{S}$$

τ_{rc} = reference shear stress for sediment class c [Kg m^{-1} s^{-1}]

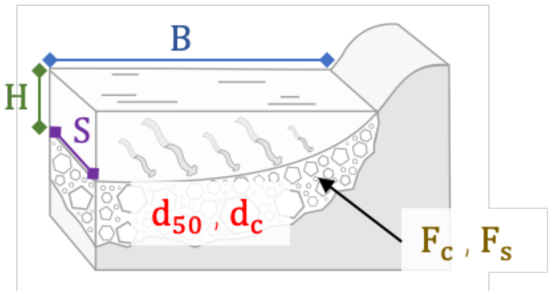
$$\tau_{rc} = \tau_{rm} \left(\frac{\mathbf{d_c}}{\mathbf{d_{50}}}\right)^{\gamma}$$

τ_{rm} = reference shear stress for the mean size of the bed surface sediment [Kg m^{-1} s^{-1}]

$$\tau_{rm} = \rho\, g\, R\, \mathbf{d_{50}}\, (0.021 + 2.18\, \boldsymbol{S})$$

Where:

- $\mathbf{B}$ = Active channel width [m];
- $\mathbf{d_c}$ = grain size of class c [m];
- $\mathbf{d_{50}}$ = mean class grain size [m];
- $\mathbf{H}$ = average flow depth [m];
- $\mathbf{S}$ = channel slope;
- $\mathbf{F_c}$ = Fraction of class c in the bed surface sediment;
- R = submerged specific gravity of sediment;
- g = gravity acceleration;
- ρ = water density;
- ρ_s = sediment density
- γ = hiding factor



Supplementary material 2: The Ferguson hypothesis

The hypothesis used by Ferguson et al. (2015) assumes the **river sediment regime to be in an equilibrium state**, i.e. the **bed load transport capacity in each reach is theorized equal to the incoming sediment flow** from the reaches upstream.

The introduction of this hypothesis in the model guarantees that **the transport capacity of a reach is known if the upcoming sediment flow is known too**.

From the transport capacity, the reach GSD can be extracted by fitting a probability distribution function, in order to obtain a transport capacity formula equal to the upcoming sediment flow. The function used is the Rosin distribution, a cumulative distribution function, used to represent bed load GSDs and bed material distribution (Shih & Komar, 1990).

As a result of this hypothesis, **the total sediment flow passing through the network is constant**, increasing only after confluences where the fluxes sum. However, since the transport capacity is measured for each sediment class, **single grain classes can be deposited and entrained**. In each reach, to maintain equilibrium, the deposition of some classes is compensated by the entraining of others.

For each discharge scenario, a new set of GSDs are optimized for each reach. **The annual distribution is then found as the average of the GSDs for all discharge percentiles**, weighted by the fraction of the annual sediment flow in the reach that is transported in each scenario.

With Ferguson's hypothesis, **the sediment routing in the model is initiated by the transport capacity of the source reaches**, i.e. the **reaches without any other segment upstream**, which is needed to identify the transport capacity of all the downstream reaches and their GSDs. To measure it, we need to define the GSDs of the source reaches a-priori, as described in **slide 17**.