MANNIGSEQ-BOULDERSFORPALEOHYDROLOGY

Matlab® code for paleo-hydrological flood flow reconstruction in a fluvial channel: first-order magnitude estimations of maximum average flow velocity, peak discharge, and maximum flow height from boulder size and topographic input data (channel cross-section & channel bed slope).

I. List of files

allochthonous_boulders_for_paleohydrology.m
paleo-hydrological flow reconstruction from boulder size in a fluvial channel using input data from surveyed boulders and associated channel reaches

boulders_import_template.xlsx
Excel® table for boulder data input using allochthonous_boulders_for_paleohydrology.m

topoprofile_import_template.xlsx
® table for topographic data input using allochthonous_boulders_for_paleohydrology.m

plot_Q_and_h.m
plotting peak discharge and maximum flow height estimation results after using allochthonous_boulders_for_paleohydrology.m

compare_VQh.m
a range of boulder sizes and an example topographic input (channel cross-section and channel bed slope) allow for comparison of three different approaches using boulder size for paleo-hydrological reconstruction in a fluvial channel

empiricalCosta1983.m
Matlab® function for calculations after Costa (1983), empirical approach

Clarke1996.m
Matlab® function for calculations after Clarke (1996), force balance approach

AlexanderCooker2016.m
Matlab® function for calculations after Alexander & Cooker (2016), force balance approach with an additional impulsive force provoked by unsteady flow

manningseq.m
Matlab® code adopted from Rosenwinkel et al. (2017, Supplementary Materials) which allows to solve the Gauckler-Manning formula for the input of an arbitrary and irregular shaped channel morphology by utilizing a numerical optimization scheme

fminsearchbnd.m
the function fminsearchbnd.m by John D'Errico is available on the Mathworks® File Exchange (https://de.mathworks.com/matlabcentral/fileexchange/8277-fminsearchbnd-fminsearchcon)

LambFonstad2010.m
Matlab® function for calculations after Lamb & Fonstad (2010), this approach was first considered but later not incorporated in calculations of allochthonous_boulders_for_paleohydrology.m and compare_VQh.m, see explanation below

II. Fundamental assumptions

Allochthonous boulders are originating elsewhere, they must have been transported to the place where they are found today (Webster's New World College Dictionary, 1999). Boulders in a fluvial channel this code-package will be applied to should be at best allochthonous, because transport of clasts over certain distance is characteristic of mass movement events. However, the possibility surveyed boulders are erratics transported by a glacier in the past needs to be ruled out. A good indicator to distinguish allochthonous boulders from the ones derived from locally outcropping bedrock is lithology. Transport processes of mass movement events are diverse and boulder transport by other mass movement processes than flows can occur: falls, topples, and slides (Hungr et al., 2014). Make sure boulders did not simply topple into the fluvial channel or were excavated by erosion from mass wasting deposits at the banks. High degree of roundness indicate fluvial transport (e.g. Wentworth, 1919; Zingg, 1935 and many others).

If boulders show substantial evidence of fluvial transport possible flow mechanics need to be distinguished further: A continuum transition from “clear” water floods to extremely dense fluid-solid mixtures, known under the well-established term debris flow, exists depending on the amount of sediment entrained into a flow (e.g. Stini, 1910; Hutchinson, 1995; Costa, 1984). The amount and characteristics of sediment not only have direct impact on flow density, but also on flow mechanics (e.g. Pierson & Costa 1987). In flows of transitional stage (40 – 70 wt. % sediment entrained, 1300 - 1800 kg/m^3 bulk density), known as “hyper-concentrated flows” or “debris floods” non-Newtonian, plastic fluid behaviour and laminar flow can arise due to the establishment of shear strength in the fluid material (e.g. Pierson & Costa 1987). However, if sediment entrainment stays in the lower realm of this “hyper-concentrated“ range, flow mechanics are still adequately approximated by Newtonian, turbulent flow of a “clear” water flood and discharges remain in the same order, although the total amount of sediment transported is substantial (Costa, 1984; Pierson & Costa, 1987; Pierson, 2005; Wang et al., 2009; Hungr et al., 2014). All the paleo-hydrological calculations performed in this code package are based on the assumption of turbulent, Newtonian fluid flow without shear strength. This includes also the empirical coefficients adopted from literature (see approaches below).

Here a bulk density of 1500 kg/m^3 for the fluid is considered as an upper bound where Newtonian, turbulent flow mechanics are still a valid assumption for paleo-hydrological reconstruction of boulder transporting high-magnitude flood events. 1500 kg/m^3 fluid density corresponds to approximately 1/3 in wt% of sediment in suspension (see Alexander & Cooker, 2016). It is possible to modify fluid density for calculation in allochthonous_boulders_for_paleohydrology.m and compare_VQh.m codes. A fluid bulk density of 1200 kg/m^3 is set as default. Values higher than 1500 kg/m^3 are not recommended in order to keep flow mechanics assumptions valid.

Another basic assumption for reconstruction of paleo flood hydraulics from grain-size in a fluvial channel is that maximum grain-size represents maximum transport competence of a flood flow (e.g. Costa, 1983; O’Conner, 1993; Wohl, 2010). The approaches described below in greater detail are following the incipient motion principle (Costa, 1983; Clarke, 1996): They compute the average velocities for turbulent, Newtonian fluid flow when a boulder of given diameter (D) initiates motion on the stream’s bed. Threshold conditions required for movement of large grain-sizes do only appear during high-magnitude flood events and maximum transported grain sizes represent maximum flow conditions in a fluvial channel. Boulder diameter and density of surveyed boulders is tied directly to maximum average flow velocity, peak discharge, and maximum flow height during a flood event. However, large grainsizes could be absent during time of maximum flooding and do not give record of maximum paleo-flow conditions. Furthermore, it is possible that boulders are transported through the channel where velocity was not maximum during the flood event. For this reason peak discharges from grain-sizes should always be considered as minimum estimates (Alexander & Cooker, 2016). The approaches explained below do not account for the possibility that average velocities, discharges and flood heights at different points along the channel during flooding can vary due to valley geometry hindering flow or obstacles on the way downstream causing short term flood water storage during the flood (ponding). For high flood magnitudes able to transport large boulders this consideration can be neglected because events likely overcome obstruction simply by fast scouring and entraining processes (e.g. Baker, 1973).

III. <u>The three approaches and Gauckler-Manning formula</u>

Empirical Costa 1983

This approach is based on a total of 17 measurements gathered from the literature by Costa (1983) in order to perform a power-law regression on diameter values bigger than 500 mm and average velocity of water flow (Eq. 1). An important consideration in this empirical calibration is the flow velocity measurements, which are compiled from a variety of sources that report disparate measurements of flow velocity, sometimes as incipient motion velocity and other times as sustained motion velocity. This distinction is important because the velocity to sustain movement is lower than to initiate motion of a sediment particle (Hjulstrom, 1935), and thus there is a great deal of uncertainty in the dataset used for the empirical calibration after Costa (1983). Another source of uncertainty in this data compilation that is worth mentioning is the grain sizes reported were sometimes measured individually or grain fractions or average values were derived from the original publications. Nevertheless, Costa (1983) assumed validity of this power law function on average flow velocity for incipient motion (V_{avg}) and intermediate grain diameter (D_i) (Eq. 1).

$$V_{avg} = 0.27 \times {D_i}^{0.40} \qquad (1)$$

Despite potential issues with consistency of data and unaccounted uncertainties, Costa's (1983) incipient motion power law allows for easy application of directly measured empirical data between flow velocity and grain diameter. Furthermore, it is the only fully empirical approach on such large grain sizes that could be found in the literature while creating this code package. Similar empirical approaches exist for smaller grain sizes, but it is unclear if such calibrations can be extrapolated to boulder diameters treated with this code package (e.g. Nevin, 1946; Fahnestock, 1963; Helley, 1969; Church & Gilbert 1975).

Clarke 1996

Clarke (1996) presents a force balance approach for paleo-hydrological reconstructions that is based largely on theoretical methods described by Costa (1983) and Bradley & Mears (1980). The approach obtains "critical" velocities for incipient boulder motion in a fluvial system. A critical force (F_C) is the minimum force necessary to initiate motion of a boulder lying on the riverbed and is considered to be equal to the resisting force holding the boulder in place (here the friction on the bed). It is in turn equal to the sum of lift (F_L) and drag forces (F_D) acting upon the boulder (Eq. 2).

$$F_C = F_L + F_D \qquad (2)$$

$$V_{avg} = 1.2 \times \sqrt{\frac{2}{C_L + C_D} \times \left\{\frac{\rho_m \times \left[\left(\frac{\pi}{6}\right) \times {D_n}^3\right] \times \left(\frac{\rho_m - \rho_f}{\rho_m}\right) \times g \times \{[\cos(S) \times \mu] - [\sin(S)]\}}{\left[\left(\frac{D_n}{2}\right)^2 \times \pi\right]}\right\} / \rho_f} \qquad (3)$$

By following Clarke (1996), always two critical velocities are derived for all the calculations assuming two different boulder shapes, a sphere and a cube. The computations are different in terms of assumed grain size geometry (volume and cross sectional area perpendicular to flow) and coefficients used. The friction coefficient (μ) for sliding cubic particles was derived from the internal friction angle of loose sandy gravel, the friction coefficient of rolling spherical particles was assumed to be one third of the ones for sliding particles (Clarke, 1996 and citations therein; Eq. 3). Lift coefficients (C_L) are higher for spherical shaped grains, whereas drag coefficients (C_D) are higher for cubic shapes (see Clarke, 1996 and citations therein; Eq. 3). In theory the input coefficients should not change for different grain sizes, but will vary for different grain shapes (μ, C_L) and riverbed characteristics (μ, C_D). From the critical velocities of cubes and spheres the mean is assumed as a good representation of critical velocities for natural, fluvially transported boulders in a stream, which appear usually between sub-round and sub-angular (Clarke, 1996). Following input values for the coefficients that are the same as those presented by Clarke (1996) were used for the calculation: μ(cubic)= 0.675, μ(spherical)= 0.225, C_L (cubic) = 0.178, C_L (spherical) = 0.200, C_D (cubic) = 1.18, C_D (spherical) = 0.20. Finally, average flow velocities (V_{avg}) were considered 1.2 times higher than critical velocities for incipient boulder motion at the riverbed for shallow turbulent streams (Costa, 1983; see factor 1.2 in Eq. 3). For derivation of complex Equation 3 refer to Clarke (1996). Boulder shape is approximated by a sphere, Clarke (1996) used a nominal diameter D_n = (three major axes)$^{(1/3)}$. ρ_m is boulder density, ρ_f is fluid density, g is gravitational acceleration and S is bed-slope.

Alexander & Cooker 2016

Similar to Clarke (1996) the Alexander & Cooker (2016) approach derives flow velocities with a theoretical force balance approach. But Alexander & Cooker (2016) include an impulsive force (F_a) designed to account for "inherently unsteady" and "non- uniform" flow, especially if referring to the term "flashflood". Unsteady flow results in rapidly changing flow conditions and therefore high spatial and temporal variability of the fluid's velocity. Imagine a very turbulent flood head arriving very fast rising flow depth and velocity in a very short amount of time or surges lacking in time of arrival after the first rise of a flood (Archer & Fowler, 2015). Alexander & Cooker (2016)'s reasoning and derived approach is supported by many recent video observations of large boulder sizes transported in floods under conditions that cannot be explained by steady-flow conditions as assumed in earlier established approaches (e.g. Costa, 1983; Clarke, 1996). Methods assuming steady flow conditions tend to overestimate flow velocities (Alexander & Cooker, 2016). Boulder transport may be sustained by inertia in between individual surges during a flood. The net-force acting upon a boulder during a flood (F) is defined by Alexander & Cooker (2016) by Equation 4 as the sum of drag-force (F_d) and frictional force (F_f) subtracted by impulsive force (F_a). After rearrangement of force terms and the a priori assumption of a drag coefficient (C_d) equal to one, a term for the velocity that initiates boulder movement dependent on the rate of change in time of the fluid velocity relative to the boulder (a) can be derived (Eq. 5).

$$F = F_d + F_a - F_f \qquad (4)$$

$$V_0 = \sqrt{\frac{4}{3} \times D \times g \times \left(\left(\frac{\rho_m}{\rho_f} - 1 \right) \times \mu - k \times \frac{a}{g} \right)} \qquad (5)$$

A representative value for the acceleration (a) was considered to be 0.5 m/s^2, a value which was also applied in the calculations performed in Alexander & Cooker (2016). Here, a value of 0.4 was used for the coefficient of friction (μ), assuming friction between rolling and sliding for a sub-angular clast (French 1971). Because of Alexander & Cooker (2016)'s statement that boulders stay mostly emerged during flooding, an assumption supported by observations from flood events, velocities derived with Alexander & Cooker (2016)'s approach are assumed similar to average flow velocities and are therefore set equal ($V_0 = V_{avg}$; Eq. 5). For derivation of complex Equation 5 refer to Alexander & Cooker (2016). Boulder shape is approximated by a sphere with diameter D. ρ_m is boulder density, ρ_f is fluid density, g is gravitational acceleration and k is a dimensionless constant that depends on the shape of the boulder (k = ½ for a sphere).

Gauckler-Manning formula

The Gauckler-Manning formula was used to convert average flow velocity (V_{avg}) from the three approaches outlined above to peak discharge estimates and maximum flow heights in a fluvial channel (Gauckler, 1867; Manning, 1891). This empirical formula provides reasonable results for turbulent and Newtonian fluid flow in a conduit or an open channel and relates average flow velocity (V_{avg}) to hydraulic radius (R_H), channel slope (S) and a coefficient dependent on roughness (Manning's coefficient n). By multiplying it with the cross-sectional area of flow (A) we get Equation 6 for discharge. The hydraulic radius is given by Equation 7 with wetted parameter (P), the length of the channel section that is underneath the flow surface.

$$Q_p = V \times A = \frac{1}{n} \times A \times R_H^{2/3} \times S^{1/2} \qquad (6)$$

$$R_H = \frac{A}{P} \qquad (7)$$

A Matlab® code of Rosenwinkel et al. (2017, Supplementary Materials) was adopted which allows to solve Equation 6 for the input of an arbitrary and irregular shaped channel morphology by utilizing a numerical optimization scheme. The advantage of this approach is that river valley cross-sectional profiles obtained from topographic maps can be used in calculations without simplification of the channel geometry. For the roughness coefficient (n) a value of 0.04 s/m$^{(1/3)}$ applicable for mountain streams after Chow (1959) is set as default. It is possible to modify the roughness coefficient (n) for calculation in allochthonous_boulders_for_paleohydrology.m and compare_VQh.m codes.

Velocities employed to the Gauckler–Manning–Strickler formula are designated as cross-sectional average flow velocities. Be aware that the fluid flow velocities derived by the three different approaches mentioned above are not implicitly defined as cross-sectional average flow velocities. Costa (1983) and Clarke (1996), use an upscaling from bed or critical velocity by a factor 1.2 to estimate "average velocity". Alexander & Cooker (2016) define their velocity as fluid velocity incident on one boulder and conversion is omitted for the computations in this code package here (see “Alexander & Cooker 2016” above).

Lamb & Fonstad 2010

The approach after Lamb & Fonstad (2010) uses a combination of a modified version of the Gauckler-Manning formula (Gauckler, 1867; Manning, 1891) after Parker 1991 (a study on selective sorting and abrasion of river gravel) with a relation of critical stress for incipient motion from Lamb (2008) and citations therein and the dimensionless shields criterion (Shields, 1936). This approach computes peak discharge values directly from boulder diameters. This approach was adopted by Lang et al. (2013) on their study on erosion of the Tsangpo Gorge, Eastern Himalaya (Lang et al., 2013). In order to test their conclusions this approach with function LambFonstad2010.m was at first included into the calculations of this code package but later dismissed because this approach yielded much higher values than calculated with empirical and theoretical approaches after Costa (1983), Clarke (1996) and Alexander & Cooker (2016).

The approaches used by Costa (1983), Clarke (1996) and Alexander & Cooker (2016) give values in the same order of magnitude for average flow velocities, peak discharges, and maximum flow heights, but these values deviate still to some extent from each other. Due to the consistency of the results using these approaches, they can be considered reliable. The most recently published study by Alexander & Cooker (2016) produces the lowest values by including the more advanced impulsive force consideration into their formulation (see “Alexander & Cooker 2016” above). Therefore their values could potentially be more representative than values from the other two approaches. Further, Alexander & Cooker (2016) discuss numerous possible sources of errors that could affect a paleo discharge estimation from boulder sizes (see citations therein). They mention the fact that large boulders that are observed in a recent video record of flash floods are transported in floods of considerably smaller magnitude than established paleo-flood reconstruction approaches from boulder sizes would suggest (including approaches after Costa, 1983 and Clarke, 1996).

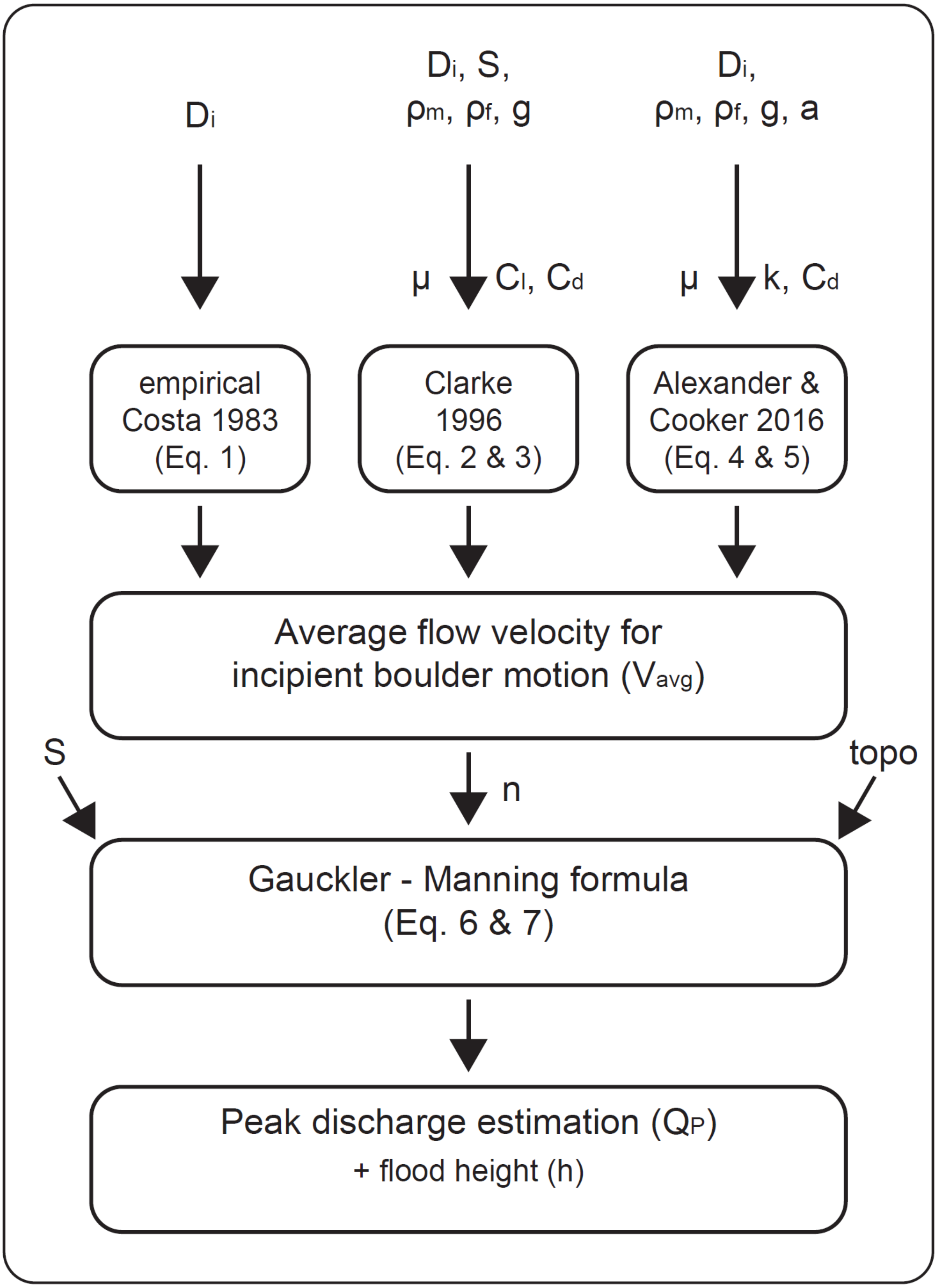

Figure 1: Flow-chart showing steps of computation for allochthonous_boulders_for_paleohydrology.m and compare_VQh.m codes. General input parameters on very top together with input coefficients below next to arrows. Compare with equations above. Topographic input (topo, S) is not added until Gauckler-Manning formula is applied.

IV. Input data

For the boulder diameter input you should aim for a value that represents the boulder shape well. An intermediate or nominal diameter, which is the diameter of a sphere having the same volume than the boulder, is recommended (use Wadell (1932) and Krumbein (1941) as reference). At best the length of three primary-axes of a boulder (longest, intermediate, shortest) can be directly measured in the field with satisfying accuracy, but often values turn out to be unreliable and inconsistent due to logistical challenges in making accurate measurements. Determination of reliable 2D intermediate axes from high resolution imagery in bird's eye view can be an option to overcome this challenge. Boulder rock material densities are possibly as well estimated in the field by mineral analysis or resolved from literature after assigning a lithology to a boulder.

Topographic input requires simplification of a complex channel morphology in an appropriate way to find adequate input parameters. As input parameters for this code package (1) a vertical profile cutting perpendicular to the flow direction of the river to approximate the geometry of the riverbed and its adjacent slopes, and (2) the bed-slope of the riverbed is needed.

Costa (1983, p. 997) recommends following guidelines for site selection when collecting adequate topographic profiles for paleo-hydrological reconstruction:

1. A straight reach is preferred, neither expanding nor contracting.

2. The site should not be an abnormally wide or narrow, or steep or flat part of the valley.

3. At least one and preferably both valley walls should be bedrock; thin colluvium over bedrock is acceptable.

4. Valley fill should be thin so a reasonable estimate can be made of the elevation of the underlying bedrock surface.

5. Select cross-section sites close to the depositional site of boulder bars used to measure particle size and close to the point at which the discharge estimate is wanted. This may require the selection of a less favourable site, but in small basins, where discharge is estimated this is very important.

6. Measure at least two cross sections spaced about one valley width apart.

7. No major tributaries should enter the main channel between the cross-section site and the point where the discharge estimate is desired.

Additionally for the hydrological reconstructions, preference should be given to locations along the river upstream of the boulder deposits. The selection of river sections upstream is based on the assumption that boulders likely travel some distance beyond the point where hydrological conditions are conducive to continued boulder transport due to inertia. Based on this assumption, geomorphic parameters taken from points upstream of the boulder deposits are more representative of the hydrological conditions for incipient motion and transport of boulders. Make sure the profile you collect is long enough and covers both flanks of the fluvial channel fully, so maximum flow height does not exceed it when conducting calculations with this code package.

Like already mentioned in Costa (1983)'s guidelines, peak discharges and maximum flow heights should at best be calculated from average flow velocities with more than one topographic input profile for a single surveyed boulder. This is recommended to give a better representation of river morphology immediately upstream of a given boulder location by minimizing error due to peculiarities of individual topographic cross-sections. The allochthonous_boulders_for_paleohydrology.m code allows the input of multiple topographic cross sections and calculates for every single boulder an arithmetic mean of peak discharge and maximum flow height values computed with different topographic input.

A good estimation of bed slope can be easily extracted from reliable topographic maps. The extraction of valley cross sectional profiles from topographic maps sometimes only gives a rough approximation for river bed respectively flood channel morphology. Adjacent terrace flats and channel widths are crudely represented when topographic maps have only low resolution. Riverbed morphology and adjacent topography represented by topographic input are crucial for paleo-hydraulic calculations.

Be aware that riverbed geometries must have changed over time due to periods of river incision or aggradation. The present-day cross-sectional profile likely represents a modified version of the channel geometry at the time of boulder transport and emplacement, and, thus, the paleo-hydraulic reconstruction with present-day geometries incorporate a certain amount of unconstrained error.

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Nancy, 24/01/2021 (updated with license)

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