Entrainment and deposition of boulders in a gravel bed river

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Abstract.

~~Rivers transports coarse sediment (gravel, cobbles, or boulder) as bedload. During a flood, when the discharge is high enough, the sediment grains move by rolling and bouncing on the river bed. Measuring bedload transport in the field is notoriously difficult. Here, we~~We propose a new method to characterize bedload transport ~~by floods~~in rivers. Using a drone equipped with a high resolution camera, we recorded yearly images of a bar of the Vieux-Habitants river, a gravel-bed river located on Basse-Terre Island (Guadeloupe, French West Indies). These images, combined with high frequency measurements of the river discharge, allow us to monitor the evolution of the population of boulders on the river bed. Based on this dataset, we estimate the smallest discharge that can move the boulders, and calculate the ~~effective transport~~ time ~~of~~during which the river~~.~~ effectively transports them. We find that the transport of boulders occurs ~~about~~for approximately 10 hours per year. When plotted as a function of ~~this~~the effective transport time, ~~likelihood of a given boulder remaining~~the population of boulders that were in place at the ~~same location~~beginning of the survey decreases exponentially, with an effective residence time of approximately 17 hours. ~~We then propose a rough~~Based on our results, we suggest a new method to estimate ~~of the average number of boulders that the river carries every year~~the bedload discharge in gravel bed rivers.

1 Introduction

Rivers collect sediment from the surrounding hillslopes~~,~~ and carry it down to the oceans (Leopold ~~et al., 1995~~and Emmett, 1976). The resulting sediment flux is often intermittent: only during floods does the river exert ~~on its bed~~a force strong enough to move the sediments of its ~~sediment~~bed (Phillips and Jerolmack, 2014; Philipps et al., 2018). Flood after flood,~~ and~~ a river gradually exports sediment out of its catchment. The frequency of ~~the~~ floods and the quantity of sediment ~~they transport~~that each of them transports thus set the erosion rate ~~of~~within the catchment (Wolman and Miller, 1960).

The fate of a particle entrained during a flood depends on its size. Fine sediments are carried in suspension. Coarse ~~ones~~sediments, conversely, travel as bedload: they roll, slip and bounce on the river bed, until they eventually settle down. This process is inherently stochastic (Einstein, 1937). A turbulent burst or a collision with a travelling grain can dislodge a particle from the bed (Charru et al., 2004; Ancey et al., 2008; Houssais and Lajeunesse, 2012). Once in motion, the particle's velocity fluctuates and its eventual deposition is, again, a random process (Lajeunesse et al., 2010; Furbish et al., 2012). Even in a steady flow, a sediment particle ~~idles on the bed~~spends most of ~~the~~its time at rest on the bed; its journeys downstream are rare and short events (Lajeunesse et al., 2017). Overall, the combination of these stochastic events generates a downstream ~~flux~~discharge of sediment, referred to as "bedload transport", whose intensity depends on the properties of the flow, and on the ~~grain~~ size, density, and shape of the sediment particles (Einstein, 1950; Bagnold, 1973, 1977).

Bedload transport accounts for a large part of the sediment load exported out of mountainous catchments (Métivier et al., 2004; Meunier et al., 2006; Liu et al., 2008). It carves the channel of bedrock rivers, controls the shape and size of alluvial rivers, and generates ripples, dunes, bars and terraces (Gomez, 1991; Church, 2006; Seminara, 2010; Devauchelle et al., 2010; Aubert et al., 2016; Métivier et al., 2017; Dunne and Jerolmack, 2020; Abramian et al., 2020). In the field, geomorphologists measure bedload by collecting the moving particles in traps or baskets (Helley and Smith, 1971; Leopold and Emmett, 1976; Habersack et al., 2016). These direct measurements are laborious, and sometimes risky. These difficulties have motivated the development of alternative methods. One may, for example, estimate the intensity of bedload transport from the acoustic or seismic noise it generates (Burtin et al., 2008, 2011, 2014; Turowski and Rickenmann, 2009; Mao et al., 2016). However, the calibration of these ~~sismic~~seismic and acoustic proxies still requires direct measurements (Gimbert et al., 2014; Thorne, 2014; Burtin et al., 2016).

An alternative is to monitor the displacements of individual particles (Dietrich and Smith, 1984). These tracers – painted boulders or Radio Frequency Identification Passive Integrated Transponders (RFID PIT) inserted into the boulder– travel with the flow during floods (Cassel et al., 2020). Between two floods~~, however~~, one may look for the tracers on the exposed river bed. By repeating this procedure, one gradually reveals the trajectories of the tracers. Although laborious, this method provides reliable information, without perturbing the flow. Tracer particles have been used to evaluate the storage of particles in the sediment bed (Haschenburger and Church, 1998; Bradley, 2017), and to estimate the distance that a bedload particle travels before it settles down~~.~~ (Ferguson and Wathen, 1998; Martin et al., 2012). ~~In~~When their number is large~~ numbers~~, tracers form a plume, which disperses as it travels downstream (Bradley and Tucker, 2012; Phillips and Jerolmack, 2014). ~~We can~~One may then infer the mean bedload ~~flux~~discharge from the ~~deformation~~elongation of this plume (Lajeunesse et al., 2018).

Measuring bedload transport, nonetheless, remains arduous, and some questions are still open. On average, how often can a river transport its coarsest sediment? How long does a boulder remain on the river bed? We propose a new approach to address these questions~~ with a new approach~~. Instead of tracking the particles when they travel, we monitor the evolution of their population at a fixed location. In that sense, our method can be called "Eulerian". Using a drone, we recorded yearly images of the bed of ~~a tropical volcanic island~~the Vieux Habitants river (section 2), a gravel-bed river located in Basse-Terre Island (Guadeloupe, French West Indies). Combined with high frequency measurements of the river discharge, these images allow us (1) to follow the population of boulders that make up the bed, (2) to ~~characterize the bedload transport in this river and its evolution over eight years (section 3). Finally, using these observations, we propose an estimate of the intensity of bedload~~

~~transport averaged over a year, which include the contribution of hurricanes (section 4).~~determine the threshold discharge above which the flow puts these boulders into motion (section 3), and (3) to estimate the residence time of boulders in the river bed.

2 Field site, measurement and processing

We conducted our investigation on Basse-Terre Island, a volcanic island of the Guadeloupe archipelago, which is part of the subduction arc of the Lesser Antilles (Feuillet et al., 2002 - Fig. 1a). ~~The~~Basse-Terre's climate~~ of Basse-Terre~~ is tropical, with daily temperatures between 24 and 28 °C, and an average rainfall rate of about 5200 mm y^{-1}. Rains occur mainly as short and intense events. During the rainy season, which extends from June to January, storms and hurricanes are frequent, and the rainfall rate may reach up to 590 mm day^{-1}. As a result, the discharge of rivers varies abruptly, with frequent flash floods.

Rad et al. (2006) estimated the erosion rate of several Basse-Terre catchments~~,~~ based on the chemical composition of the dissolved load. They found that it varies between 800 and 4000 t km^{-2} y^{-1}, or, equivalently, 0.3 and 1.5 mm y^{-1} (for a rock density of about 2900 kg m^{-3}). These values are consistent with the volume of sediment mobilized by landslides during extreme climatic events (Allemand et al., 2014). They place Basse-Terre Island amongst the fastest eroding places on Earth (Summerfield and Hulton, 1994). This observation led to the creation of the “Observatoire de l’Eau et de l’éRosion aux Antilles” (ObsERA), an observatory which monitors erosion within the French Network of Critical Zone Observatories (Gaillardet et al., 2018). Our field site is located in the Vieux-Habitants catchment which is monitored by ObsERA.

The Vieux-Habitants river (Fig. 1b) drains a 30 km^2 watershed on the leeward (West) side of the island. Most of the watershed, made of andesitic lava and pyroclastic deposits aged from 600 to 400 ky, is covered with a dense rain forest (Samper et al., 2007). The Vieux-Habitants river flows over 19 km, from its headwater at an altitude of 1300 m, down to the Vieux-Habitants village, where it discharges into the Caribbean Sea. The channel is made of bedrock, partly covered ~~by~~with a thin layer of alluvial sediment. Five kilometers from the sea, the river turns alluvial, and its slope gradually decreases. Our field site is a reach of the Vieux-Habitants river located 3 km from the sea, at an elevation 45 m a.s.l. There, the river bed is alluvial and the channel, ~~confined~~meanders between two steep banks about 2.5 m high~~, meanders~~. A large boulder bar, 300 meters long and 35 meters wide, ~~occupies~~lies on the inner side of the channel (Fig. 1c, d).

The *Direction de l'Environnement, de l’Aménagement et du Logement* (DEAL-Guadeloupe) operates a stream gauge, at the Barthole station, three kilometers upstream of our field site (Fig. 1b). This station has been measuring the river discharge every ten minutes for more than 15 years, except for an interruption between 2009 and 2011. As no major tributary joins the main stream between Barthole and our field site, we shall assume that the data acquired in Barthole ~~provide~~provides a reasonable estimate of the river discharge at our site.

~~A statistical analysis of the~~The data acquired between 2011 and 2018 reveals that the discharge stays below 10 m^3 s^{-1} ~~during 90~~for 91% of the time (Fig. 2a). In this low flow state, the boulder bar ~~surfaces~~emerges and the river flows in a channel that forms between~~ the right side of~~ the bar and the left bank of the river (Fig. 1d). There, the water depth is about 0.3 m, but may locally exceed 0.7 m (Fig. 1c, d). Floods are characterized by a steady increase of the discharge during 1 to 6 hours, followed by a recession that lasts typically 4 to 18 hours (~~Guérin et al., 2018). Although frequent, their intensity rarely exceeds 50 m^3 s^{-1} (Fig. 2b): between 2011 and 2018, the river discharge stayed above 50 m^3 s^{-1} during 60 hours in total (Fig. 2a).~~Fig. 2b - Guérin et al., 2018). The largest flood ever recorded in Barthole occurred during hurricane Maria, from September 18 to September 19, 2017. The water discharge then reached more than 250 m^3 s^{-1}, flooding not only the bar but also the river's banks. After the hurricane, the river returned to its normal course, along the ~~right~~left side of the bar.

To understand how floods affect the ~~river~~river's bed, we acquired aerial images of our field site with ~~a camera carried out in a~~an uncrewed hexacopter ~~Unmanned~~ Aerial Vehicle ~~(~~named DRELIO ~~-~~(for *DRone ~~hELIcoptere~~hELIcoptère pour l'Observation de l'environnement*). This device, specially designed for tropical conditions, is capable of flying in steep, densely vegetated watersheds, ~~with dense vegetation~~ and requires only a small takeoff area (Delacourt et al., 2009). It carries a high resolution camera. We started working in 2011, with a Nikon D700 reflex camera, equipped with a 35 mm lens. In 2016, we replaced ~~the camera~~it with a Sony Alpha 7 reflex, still in use at present. As a result, the resolution of our images improved from 0.04 meters/pixel in 2011 to 0.02 meters/pixel starting from 2016.

From 2011 to 2018, we performed ~~eight~~8 field campaigns ~~and followed~~following the same procedure. We flew DRELIO at an elevation of 80 m above the river bed, and used the on-board camera to acquire a series of images that covered the entire boulder bar~~. At this altitude, the~~ with an 30% overlap between two neighboring images~~ is about 30 %. Four to six images are therefore enough to cover the whole bar. After~~. Using the MicMac Photogrammetric suite (Rupnik et al., 2017), we computed for each campaign~~, using a raster graphic editor, we drew~~ a Digital Surface Model (DSM) and an orthoimage of the bar. An orthoimage is an image from which the ~~contours~~distortion due to relief has been suppressed. Two georeferenced orthoimages of the same surface can be superimposed. Each orthoimage is georeferenced using fixed ground control points, whose coordinates are measured by Differential Global Navigation Positioning System. The resolution of the orthoimages ranges from 0.04 m to 0.02 m depending on the acquisition year. However, the georeferencing is not perfect and the series of diachronic orthoimages do not exactly overlap. We selected the 2012 orthoimage as a base image on which we warped the other orthoimages. We then draw the contour of the boulders visible on each ~~image. The~~ orthoimage using a raster graphic editor. The diameter of the smallest ~~grains~~ visible ~~on our images are 2 centimeters large.~~grains is at least 5 pixels (0.1 to 0.15 m). On the bar, however, most boulders have a diameter larger than 0.2 meters, and ~~many~~some are larger than 1 meter~~.~~ (Terry and Goff, 2014). In practice, we ~~restricted~~restrict our analysis to boulders with a diameter larger than 0.5 meters, as they are clearly distinguishable on the images. Using ~~a~~an open-source Geographical Information ~~Software (GIS~~System software (QGis), we ~~vectorized~~vectorize the contours of these boulders and ~~used a series of reference points to calibrate the scale of the resulting data. This method allowed us to~~ calculate ~~the~~their exposed area~~ of each boulder~~, A, from which we ~~deduced its effective~~deduce the boulder equivalent diameter, defined as the diameter D of a disk with the same surface area, $D = 2\sqrt{A/\pi}$.

The error on the surface is between 15 and 20 % for the smaller diameters. With this method, we obtain 8 diachronic superimposable orthoimages and 8 vector files of the boulders shapes, position and equivalent diameter.

~~Following this procedure, we produced a total of eight GIS, once per year from 2011 to 2018. Each GIS consisted in (1) a series of images of the bar warped around the image of the center of the bar, (2) the contours of the boulders of diameter larger than 0.5 m.~~ Figure 3 shows a close view of two ~~of these GIS~~orthoimages, in the region of the bar delineated by the red rectangle in Fig. 1d. The first ~~GIS~~orthoimage was acquired in March 2012 (Fig. 3, left) and the second one in June 2013 (Fig. 3, right). In both cases, the flow in the river was low, and the water level, partly visible in the upper part of the images, was about the same. The comparison between these two ~~GIS~~orthoimages reveals some changes at the surface of the bar. Several boulders (yellow contours on Fig. 3), ~~at repose~~lying on the bar in 2012, are not visible anymore in 2013: they ~~have been~~were entrained downstream by the river, ~~at some time~~sometime between our two acquisition campaigns. Conversely, we also observe~~ the appearance~~, in 2013, ~~of s~~several boulders that were not present in 2012 (red contours on Fig. 3): these boulders must have been deposited on the bar, ~~at some time~~sometime between the ~~acquisitions of the~~ two images. Finally, the rest of the boulders (blue contours on Fig. 3) remained in place. The comparison between two consecutive GIS therefore allows us to identify the fate of each ~~block~~boulder. Based on this method, we attribute to each boulder ~~contour, in~~of each ~~GIS~~image, a label which specifies whether ~~it~~the boulder was already in place during the previous campaign, or if it ~~has been~~was deposited recently. Some cases turn out to be ambiguous: a few boulders disappeared and then reappeared on more recent images, as floods covered them with sediment, before exposing them again. Those ambiguous cases were duly labelled and the corresponding boulders were considered immobile. Following this procedure, we end up with a dataset that contains the position and the size of all the boulders larger than ~~50cm~~0.5 m. We also know whether ~~the boulder~~each of them stayed in place or ~~if~~whether, and when, it was deposited ~~and/~~or entrained away. In short, we have turned the boulders into tracers. In the next section, we ~~analyze~~use this dataset to characterize the transport of boulders in the Vieux-Habitants river.

3 Results

3.1 Structure of the bar: mobile and consolidated layers

Our data show that entrained and deposited boulders are uniformly distributed over the whole bar. There is no particular place from which boulders ~~would be~~were preferentially exported, nor onto which they ~~would be~~were preferentially deposited. This suggests that, during floods, bedload transport is uniform over the bar.

~~We~~Our dataset also ~~observe~~reveals the existence of two families of immobile boulders. ~~Some of them~~The first one corresponds to boulders that were deposited ~~at the surface of~~on the bar during the course of our survey~~. They~~, and remained immobile for several years, until the river entrained them again. ~~Others~~The second one corresponds to boulders that remained immobile during the whole survey. The latter are partially buried in a matrix of smaller sediment and appear to belong to a stable underlying base layer, that spans over the entire bar. ~~This observation is~~These observations are consistent with ~~laboratory~~

experiments, in which a layer of mobile grains travels over a static sediment bed (Charru et al., the concept of active layer (e.g. Church and Haschenburger, 2006).-We therefore2004, Lajeunesse et al., 2010). Although mobile grains regularly settle on the static bed, the flow eventually dislodges them and set them back in motion. Based on these observations, we interpret our field datathem as the result of the existence of two layers of boulders: (i) a discontinuousan active surface layer of mobile boulders, and (ii) an underlying basal layer of static ones. Interestingly, laboratory experiments report a similar division between an active layer of mobile grains, that regularly settle on the bed until the flow eventually dislodges them and set them back in motion, and a layer of static grains (Charru et al., 2004, Lajeunesse et al., 2010). In the following, we focus on the properties of the layer of mobile boulders.

3.2 Granulometric distribution

The size of We start our analysis by focusing on the mobilemotion of boulders at the surface of the bar ranges fromsize between 0.5 toand 2 meters. To characterize their distribution, we divide this interval into 6 uniformsix 0.25 m-wide bins, and distribute the boulders in each one, according to their sizeequivalent diameter. We then compute the dimensionless surface density of each class *i*, defined as the number of grains per unit surface, normalized by the area of a grain:

$$\tilde{\sigma}_i = \frac{N_i \times \pi D_i^2}{S} \qquad (1)$$

where N_i is the number of boulders in class *i*, D_i is their effectiveequivalent diameter, and S=2000 m^2 is the area of the bar. The dimensionless surface density σ_i can also be interpreted as the proportion of the bar area occupied by the boulders of class *i*.

The number of boulders in each class and the corresponding surface density vary from year to year. To account for these variations, we compute these two quantities for each field campaign, and represent the results with in the form of a box plot (Fig. 4a). We find that the surface density does not change significantly with time: in of each class, varies by less than 27% around its variations are negligible with respect to the median value. This suggests that, at first order, the The size distribution of the boulders thus does not change significantly with time, but appears to be roughly at equilibrium. This equilibrium is in steady state. The surface density, however, rapidly decreases with grain size (Fig. not static, but dynamic. Indeed, distinguishing4a). Boulders within 0.5 and 0.75 m in diameter – named D_1 thereafter - dominate the surface of the bar, at least in the range of diameters accessible to our measurement method. For this class, the median value of the dimensionless surface density is $\tilde{\sigma} = 0.055$. Returning to dimensional quantities, this corresponds to a surface density of $\sigma = 0.23$ boulders m^{-2}, or, equivalently, a total number of about 600 boulders over the 2000 m^2 of the bar.

That the size distribution of the boulders is almost in steady state is an unexpected observation. To understand it, we distinguish, within each class, the boulders freshly deposited (Fig. 4a, green boxes) from those that were already in place during the preceding campaign (Fig. 4a, yellow boxes), and calculate their surface density. The result varies within boulder size (Fig. 4a). Each year,) shows that about half of the population of D_1 boulders is made up of freshly deposited

~~sediment~~renewed each year (Fig. 4a). In ~~this class, the boulders are highly mobile, but~~short, the number of boulders entrained by floods balances, on average, the number of fresh boulders deposited on the bar, thus maintaining constant their surface density (Fig. 4b).

Finally, our analysis shows that the surface density rapidly decreases with grain size (Fig. 4a). ~~This is not true for larger boulders. Indeed, the proportion of freshly deposited boulders rapidly decreases with the grain size, and eventually vanishes for boulders larger than 1.75 meters (Fig. 4a). The mobility of a boulder thus decreases with its size. It is because large boulders are seldom mobilized that their surface density remains constant in our dataset. We thus cannot assess whether their population is effectively in steady state.~~

~~Given that the D_1 boulders are, at the same time, the most abundant and the most mobile, we shall now concentrate our analysis on this class of boulders. In the next section, we start by estimating the threshold discharge necessary to entrain them.~~

With a surface density $\sigma = 0.23$ boulders m^{-2}, or equivalently, a total number of about 350 boulders over the 2000 m2 of the bar, boulders of size 0.5 to 0.75 m dominate the bar, at least in the range of diameters accessible to our measurement. The transport rate of these boulders is also sufficiently high to allow for significant statistics. In the following, we shall therefore focus on the transport of boulders of size 0.5 to 0.75 m. Before we do so, however, we first need to evaluate the threshold discharge above which these boulders are set in motion. This is the topic of the next section.

3.3 Threshold for the initiation of transport

~~The boulders of our field site move only when the discharge of the Vieux-Habitants river is large enough. Based on our 8 GIS, we~~Based on our dataset, we can identify the largest boulders deposited on, or entrained from, the bar between two consecutive campaigns. ~~We then plot~~Plotting their diameter as a function of the maximum water discharge between ~~the~~two campaigns ~~(Fig. 5). We~~, we find that the size of these boulders ~~correlates well~~increases with the maximum discharge~~.~~ (Fig. 5). Assuming that the largest boulders are transported when the discharge is at its highest, the resulting curve provides a reasonable estimate of the threshold discharge beyond which ~~transport takes place, as a function~~grains of ~~grain~~a given size~~, for boulders larger than about 0.8 m. The~~ are entrained by the flow. For lack of sufficient data, however, ~~does not allow us to constrain~~we cannot estimate the threshold discharge of boulders smaller ~~boulders~~than 0.5 m. Instead, we shall now try to evaluate it, by extrapolating from our observations~~ in terms of dimensionless quantities~~.

In practice, the threshold discharge corresponds to the discharge for which the shear stress exerted by the river on its bed exceeds a critical value (Shields, 1936). The instantaneous turbulent stress exerted on the river bed is, however, highly variable in space and in time: it depends on the flow, on the shape of the channel, on the river slope, on the bed roughness, and its measurement in the field is challenging (Henderson 1963, Parker 1978, Chauvet et al., 2014, Métivier et al., 2017, Nezu and ~~H.~~ Nakagawa, 1993). Here, to simplify the problem, we assimilate the river to a rectangular channel of width W, depth H, and slope S. Based on the Darcy-Weisbach equation, we then derive the threshold discharge required to transport a boulder (see appendix for a full derivation):

$$Q_c = W \frac{D^{3/2}}{S} \left(\Theta_c \frac{\Delta\rho}{\rho} \right)^{3/2} \left(\frac{g}{C_f} \right)^{1/2} \quad (2)$$

where $\Delta\rho = \rho_s - \rho$ is the difference between the density of rock and that of water, C_f is the Darcy-Weisbach friction parameter, g is the acceleration of gravity, and Θ_c is the threshold Shields parameter (Shields, 1936). Our model is crude and some of the parameters in equation (2) are difficult to estimate. Based on direct field measurements, we estimate the river width to be W=30 m. Using the DEM, we calculate its average slope and find it to be about S = 0.03. ~~We use the value Θ_c = 0.02 for the threshold Shields number (Shields, 1936). The most inaccurate of our parameters is certainly~~For the friction coefficient~~ for which,~~ we use the value C_f = 0.1, typical ~~in~~of mountain streams (Limerinos, 1970). ~~Despite these shortcomings,~~A fit of equation (2) to our data reasonably accounts for our observations (Fig. ~~5). Encouraged by this result, we use equation (2) to calculate the threshold discharge of D_1 boulders. We find~~5), and yields a threshold ~~discharge between 38 and 52 m^3s^{-1}, with~~ Shields stress Θ_c=0.032, which falls in a ~~medium value of 45 m^3s^{-1}. In the next section, we use this value to estimate the time during which the river effectively transports these boulders.~~realistic range (Buffington and Montgomery, 1997; Lamb et al.,2008).

Encouraged by this result, we use equation (2) to calculate the threshold discharge of the boulders of size 0.5 to 0.75 m. We find a threshold discharge between 24 and 69 m^3s^{-1}, with a value of 45 m^3s^{-1} for the intermediate Shields number of 0.032. In the next section, we use this value to estimate the time during which the river effectively transports these boulders.

3.4 Effective transport time

~~In the previous section, we calculated that D_1 boulders~~ Boulders of size 0.5 to 0.75m move only when the river discharge exceeds ~~about~~the threshold value of 45 ~~m^3 s~~m^3s^{-1}~~. Based on this result, we now evaluate the~~ calculated in the previous section. Their effective transport time~~, defined as~~ is therefore the cumulated time that the river spends above this threshold (Fig. 6). We find that ~~the effective transport time~~ it amounts to a total of 85 hours ~~over~~for the period 2011 to 2018. The ~~proportion~~ time fraction during which the river is above the entrainment threshold is thus I= 0.12%. ~~On~~ This means that, on average, ~~these~~ boulders ~~thus~~can move during about 10 hours each year.

The effective transport time depends on the occurrence of floods, and therefore, on the distribution of rainfalls. As the latter varies from year to year, so does the effective transport time (Fig. 6): the river spent less than 5 hours above ~~threshold~~45 m^3s^{-1} between 2014 and 2016 (an unusually dry period). Conversely, it spent 32 hours above ~~the threshold~~45 m^3s^{-1} between 2017 ~~to~~and 2018, a period that includes ~~the~~ hurricane Maria. Even ~~then~~during those years, the annual effective transport time did not exceed 0.36% of the ~~total time~~year that is about 30 hours~~ each year~~. On a tropical volcanic island like Guadeloupe, ~~the~~ boulders move only during short periods of time, whose cumulated duration depends on the frequency and the intensity of the storms~~ that hit its catchments~~.

3.5 Evolution of the population of boulders

So far, we have focused on ~~mobile boulders, their~~ the threshold of transport~~,~~ and ~~their~~the effective transport time of boulders. We now use our data to document the evolution of their population. ~~To do so~~As in previous sections, we restrict our analysis to boulders of size 0.5 to 0.75m. We start ~~from the 2011 GIS and identify~~by identifying all the ~~D_1~~ boulders ~~that are at idle~~lying on the bar in 2011. Using ~~later images~~our dataset, we then monitor the evolution of this population. We find that ~~their~~its number decreases with the effective transport time, as ~~they~~boulders are progressively entrained by floods, and replaced with new ~~boulders~~ones (Fig. 7), an observation similar to those of Wilcock and McArdell (1997) and Harchenbucher and Wilcock (2003).

~~We repeat~~Repeating the same procedure with the boulders ~~that first appeared~~lying on the bar in 2012, and ~~in~~ the following years until 2017~~. By doing so, ~~,we ~~monitor~~end up monitoring a total of seven populations ~~in total~~of boulders. To compare their evolution, we normalize the number of boulders in each population with its initial value, and plot the result as function of the effective transport time (Fig. 7). We find that all data points gather around the same trend: the number of boulders decreases rapidly at first. With time, however, the rate gradually slows down~~ gradually~~.

~~For a given boulder size,~~As the surface density of boulders is small (σ =0.23 boulder m^{-2} - see section 3.2)~~, and~~ we expect little interaction between them during transport. Following Einstein (1937) and Charru et al. (2004), we thus assume that the number of boulders that leave the bar is proportional to the number of boulders available on its surface, that is:

$$\frac{dN}{dt} = -\frac{N}{\tau} \tag{3}$$

where t is the effective transport time, N is the number of boulders on the bar surface at time t, and τ is ~~the~~a characteristic entrainment time. The solution of Eq. (3), $N = N_0\, e^{-t/\tau}$, is a decaying exponential, of characteristic time τ, where N_0 is the initial number of boulders. Fitting this exponential solution to our data yields a good representation of the evolution of N (R^2 =0.84). We find a characteristic time τ =17 hours (Fig. 7).

The model proposed here is simplistic. It does not take into account the ~~water flow~~ variations of discharge during a ~~floods~~flood, and relies on a crude description of the threshold of transport. Yet, the exponential decrease of an initial population of boulders is consistent with the data plotted on figure 7, and we therefore expect that the value of the characteristic time τ is a reasonable estimate of the residence time of boulders on the bar, expressed in terms of the effective sediment transport time. ~~The characteristic~~This residence time ~~during which a D_1 boulder stays at rest on the bar~~ is ~~surprisingly~~ short. Expressed in terms of half-life,~~ this means that~~ it takes an effective transport time of log2 τ = 12 hours to entrain half of the boulders initially present on the bar, and to replace them with new ones.

~~4 Boulder discharge~~

~~Based on the model of previous section, we now estimate the boulder discharge in the Vieux-Habitants river. Once again, we assimilate the river to a rectangular channel. During a flood, the water discharge is above the threshold of entrainment, and the flow continuously entrains new boulders. Laboratory experiments show that, once dislodged from the bed, bedload particles travel over a characteristic flight length, L_f, before they are deposited on the bed (Lajeunesse et al., 2010; Furbish et al, 2012, 2016). If this result holds in nature, the discharge of boulders across a given section of the river is just the number of grains entrained per unit time, in a bed area of size WL_f (Fig. 8). According to equation (4), boulder~~

discharge is therefore the number of boulders at rest on this surface, $\sigma W L_f$, divided by their residence time, τ, where σ is the surface density of boulders (Einstein, 1937). Following this reasoning, we find that the volumetric discharge of boulders reads:

$$Q_e = \frac{\pi D^3}{6} \times \frac{\sigma W L_f}{\tau}, \tag{4}$$

where we assimilate the boulders to spheres of diameter D.

Equation (4) yields the instantaneous boulder discharge in terms of the effective transport time. To convert this value into an annual sediment flux, we multiply it by the proportion of time, *I*, during which the river is above the entrainment threshold:

$$Q_y = I \times \frac{\pi D^3}{6} \times \frac{\sigma W L_f}{\tau} \tag{5}$$

To calculate the sediment discharge, we need to estimate all the parameters in equation (5). In the previous sections, we found that, for D_1 boulders, the surface density is σ = 0.23 boulders m^{-2}, the residence time is τ = 17 h, and the proportion of effective transport time is I = 0.12%. To calculate the discharge, we still need to evaluate the average flight length of a boulder. Unfortunately, our measurement method does provide the trajectories of the boulders, and we thus do not have any direct measurement of their flight length. Instead, we propose a lower bound for it. During our survey, several uncommonly large boulders, of size larger than 1.5 m, disappeared from the bar. They have been entrained by a flood, between two successive campaigns. Although these boulders were large enough to be identifiable, we never detected them again. We therefore conclude that their flight length must be longer than the length of the bar, that is $L_f \gtrsim 300$ m. Based on this value, and assuming that bedload is transported across the entire river, we find a boulder discharge of 8 m^3 per hour of effective transport time, which corresponds to an annual sediment discharge Q_y = 61 m^3 y^{-1}, or equivalently, 177 t y^{-1} for a rock density of 2900 kg m^{-3}.

So far, we have restricted our analysis to boulders between 0.5 and 0.75 m (D_1 boulders). We now extend our calculations to larger boulders. To do so and for lack of direct measurements, we assume that the flight length and the residence time τ do not vary much with the boulder size. We then compute the threshold discharge of large boulders from equation (2), calculate the proportion of time, I, during which they are transported, and estimate their annual discharge from equation (5) (see table 1). We find that the D_1 population dominates the total solid load, whereas the contribution of boulders larger than 1 m is marginal. In total, the discharge of boulders in the Vieux-Habitants river amounts to about Q_y = 76 m^3 y^{-1}, that is 240 t y^{-1} from boulders between 0.5 to 2 m.

It might be tempting to extrapolate our results to boulders and pebbles smaller than 0.5 meters. This would, however, be a precarious endeavor: the detection of small boulders proved difficult on our images, and we do not have any access to their effective transport time. Besides, small boulders are probably sensitive to the bed roughness, and extrapolating their threshold discharge or their flight length from those of large boulders would be hazardous (Mao et al., 2014).

~~5.~~4. Discussion - Conclusion

To the best of our knowledge, we present the first attempt at characterizing bedload transport based on yearly UAV image acquisition. Despite — or, maybe, owing to — its simplicity, the method proves robust: the comparison of images taken one year apart allowed us to monitor the evolution of the population of boulders at the surface of the Vieux-Habitants river. Using high frequency measurements of the river discharge, ~~it was then possible to~~we determine the threshold discharge necessary to set boulders in motion, and estimate the time during which the flow ~~was strong enough to transport them. In the Vieux-Habitants river, this effective transport time amounts to 10.5 hours per year, on average. The transport of boulders is therefore a rare event. The effective transport time depends on the time distribution of rainfalls, which fluctuates from year to year. In a river like the Vieux-Habitants river, it is therefore necessary to consider the effective transport time to evaluate bedload transport.~~is strong enough to transport them. The model of threshold we use, despite its simplicity, reproduces well our observations for a realistic range of parameters.

In the Vieux-Habitants river, this effective transport time amounts to 10.5 hours per year on average, that is about I=0.12% of the time. The transport of boulders is therefore a rare event controlled by the occurrence of floods, which, in its turn, depends on the distribution of rainfalls. A change of this distribution is likely to impact the quantity of sediment transported by the river.

Einstein (1937) was the first to propose that the entrainment of bedload particles is inherently a random process. This hypothesis is at the core of the entrainment-deposition model (Charru et al., 2004; Lajeunesse et al., 2010; 2018). When expressed in terms of the effective transport time, our data are consistent with this assumption: the population of boulders on the bed of the Vieux-Habitants river decreases exponentially, as expected for a random Poisson process. The characteristic time of this decay — in fact, the residence time of the boulders on the bed — is ~~surprisingly~~ short: τ =17 hours of effective transport time~~, distributed aver about 2 years of actual time.~~ .

~~Based on our observations, we evaluate the annual discharge of boulders in the Vieux-Habitants river to be about Q_y = 240 t y^{-1}. When rescaled to the area of the Vieux-Habitants watershed, the resulting erosion rate, 8 t km^{-2} y^{-1}, is very small with respect to the 800 to 4000 t km^{-2} y^{-1} estimated from a geochemical mass balance or a geometrical reconstruction (Rad et al., 2006; Samper et al., 2007). This suggests that the solid load exported out the catchment primarily consists of sediment smaller than 0.5 m. Given the intensity of the weathering rates in Basse-Terre island, it is likely that most of the solid load is, in fact, made of fine regolith, carried in suspension in the flow.~~

~~Finally, our estimate of the boulder discharge is based on a rough lower bound of flight length. Direct measurements of this length remain an instrumental challenge to this day.~~

We suggest a method to estimate the sedimentary discharge associated to boulder transport, based on the exponential decay of a population of well-identified boulders. During a flood, entrained boulders will travel over a distance L_f that depends on the duration and on the intensity of the flood. The discharge of boulders across a given section of the river is the number of grains entrained per unit time, from a bed area of size WL_f. The boulder discharge is therefore the total number of boulders at rest on this surface, $\sigma W L_f$, divided by the residence time, τ, where σ is the surface density of boulders (Einstein, 1937). The instantaneous volumetric discharge is then the number of grains entrained by unit time, times the average volume of grains. To convert this value into an annual sediment flux, we multiply it by the proportion of time, *I*, during which the river is above the entrainment threshold. L_f is the most difficult parameter to estimate. It can be approached by using a tranport law (Lajeunesse et al., 2010) or measured in the field using RFID tracers as proposed by Phillips and Jerolmack (2014).

Code/Data availability

Discharge data used for figures 2 and 6 are available on http://www.hydro.eaufrance.fr/. UAV Images and dataset are available on Harvard Dataverse ~~https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/QRHM8E~~https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/QRHM8E

Author contributions

PA designed and performed the field measurements, and processed the resulting data. All ~~the~~ authors developed the overall ideas and were responsible for critical contributions, passing the final manuscript and editing text and figures.

Competing interests.

The authors declare no competing interests.

Acknowledgements

This work was carried out in the framework of Obsera (Observatoire de l'Eau et de l'Erosion aux Antilles). Obsera is part of OZCAR infrastructure. P. Grandjean, S. Passot, V. Robert et T. Kitou are warmly thanked for their efficiency and involvement in this work. This is IPGP contribution n°

Appendix A - Threshold discharge

Here, we estimate the threshold discharge above which the river can transport its sediment. To do so, we assimilate the channel to a rectangle of width W, depth H, and slope S. The Darcy-Weisbach equation then relates the average flow velocity V to the shear stress τ exerted on the river bed (Limerinos, 1970):

$$\tau = C_f \rho V^2 \quad \text{(A1)}$$

where ρ is the density of water and C_f is the Darcy-Weisbach friction coefficient. In steady state~~ channel flow~~, the momentum balance requires that:

$$\tau = \rho g S H. \qquad \text{(A2)}$$

At the onset of sediment motion, the Shield number, Θ, defined as the ratio between the driving force acting on the grains and the weight of a grain, must equal a threshold value Θ_c:

$$\Theta = \frac{\tau}{\Delta\rho g D} = \Theta_c, \qquad \text{(A3)}$$

where Δρ is the difference between the density of a grain and that of water, g, is the acceleration of gravity, and D is the grain size. Combining (A2) with (A3) yields the expression of the flow depth H at the threshold of entrainment:

$$H = \Theta_c \frac{\Delta\rho}{\rho} \frac{D}{S}. \qquad \text{(A4)}$$

Similarly, combining (A1) with (A2) and (~~A5~~A3) yields the average flow velocity at the threshold of entrainment:

$$V = \left(\Theta_c \frac{\Delta\rho}{\rho} \frac{gD}{C_f}\right)^{1/2}. \qquad \text{(A5)}$$

Injecting the velocity and the flow depth into the expression of the water discharge, $Q = WHV$, we find the threshold discharge above which the river can transport a boulder of diameter D:

$$Q_c = W \frac{D^{3/2}}{S} \left(\Theta_c \frac{\Delta\rho}{\rho}\right)^{3/2} \left(\frac{g}{C_f}\right)^{1/2} \qquad \text{(A7)}$$

This expression, of course, is only a crude estimate, if only because the river is not a straight rectangular channel. Nonetheless, it provides a decent approximation of the flow conditions that are necessary to initiate the transport of a given class of boulders (Figure 5).

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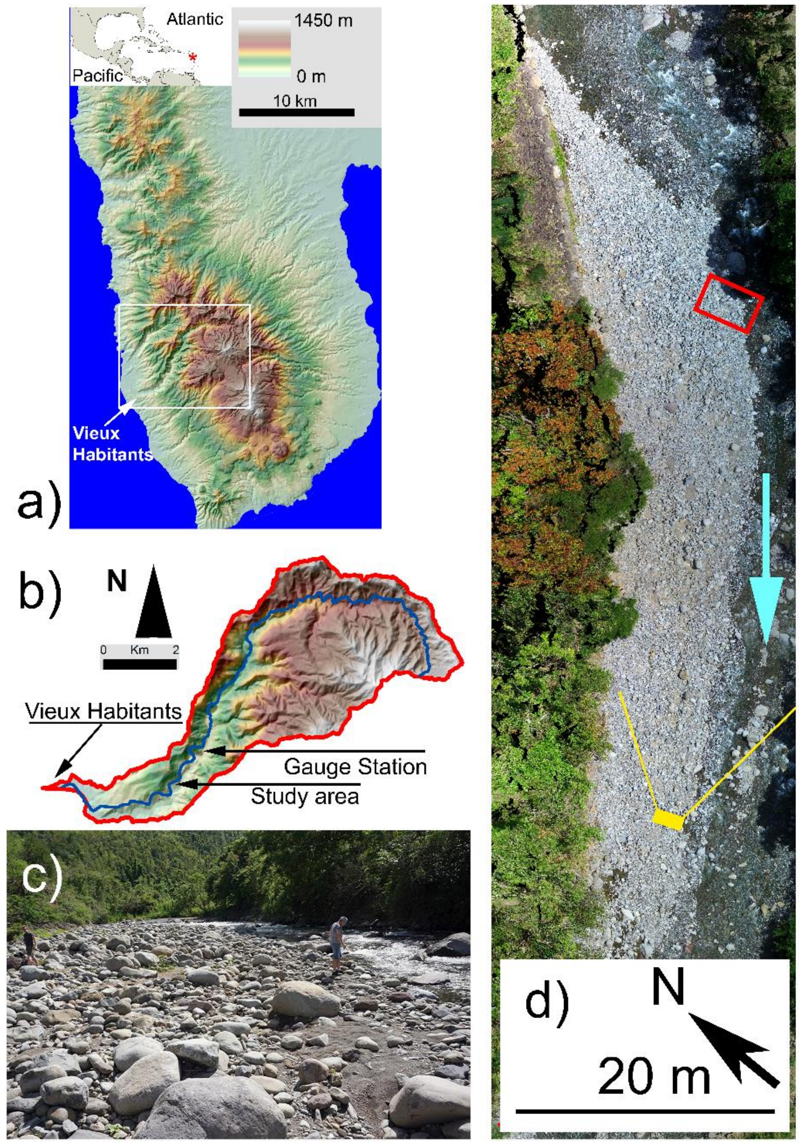

Figure 1: a) Basse Terre island in the Guadeloupe archipelago. The island separates the Atlantic Ocean in the East from the Caribbean Sea in the West. The white rectangle shows the position of the map displayed in b). b) The Vieux-Habitants river is located on the Caribbean side of Basse Terre. The watershed of Vieux-Habitants has an area of 19 km^2. The length of the river is 19 km. The water discharge is measured each 10 minutes at Barthole gauge station. The study area is located 2 km downstream of Barthole. c) A view of the bar from ground looking upstream shows the size of the boulders and their heterometric distribution. The two ~~peoples~~persons give the scale. d) The area of interest. The bar is about 300 m long and 15 to 35 m wide. It lies on the right side of the river 3 km upstream of the seashore. In fair weather conditions, the bar is bounded on its left by the channel of the river which is 5 to 10 m wide and less than 1 m deep. The boulder bar is flooded 1 to 3 times a year. The red square shows the location of Fig. 3. The position of the camera and the field of view of c) is shown in yellow. The flow direction is given by the turquoise arrow.

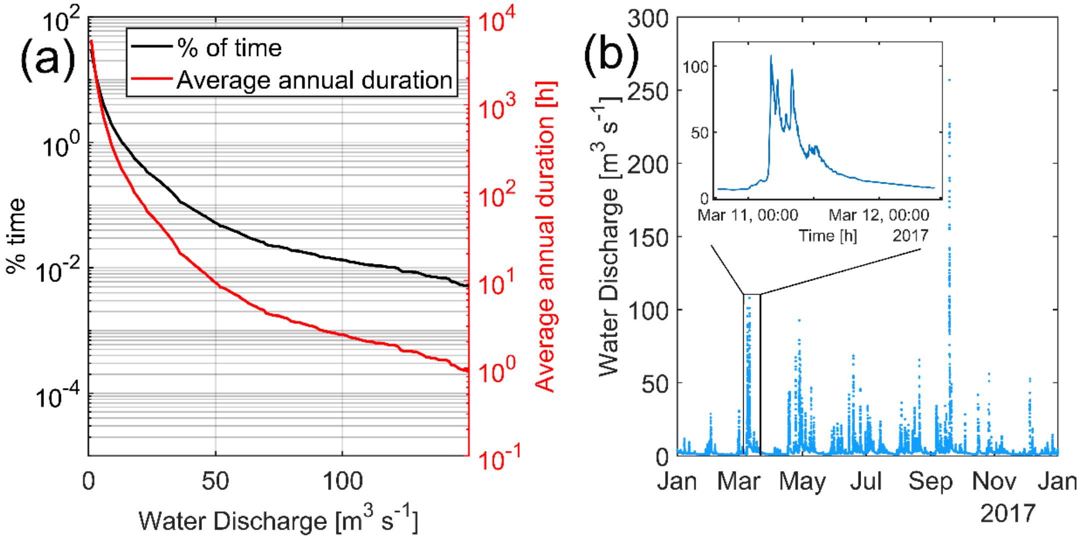

Figure 2: a) ~~Duration~~Percentage of time during which the water discharge is above a given threshold based on data from 2011 to 2018. ~~A flow of 50 $m^3 s^{-1}$ was exceeded around 60 hours during the 8 years of measurement (about 0.1% of the total time).~~ b) ~~Hydrogram~~Hydrograph of year 2017. ~~In low flow conditions, that is most~~Most of the time, ~~the discharge~~ river is in low flow conditions with less than 5 $m^3 s^{-1}$. The largest ~~discharge~~ recorded ~~in 2017~~discharge was 263 $m^3 s^{-1}$. It was reached on September 19 2017 during hurricane Maria. c) The inset shows a typical flood. The water discharge reaches its maximum in less than one hour. The peak of the flow is followed by a slow recession ~~toward low flow~~.

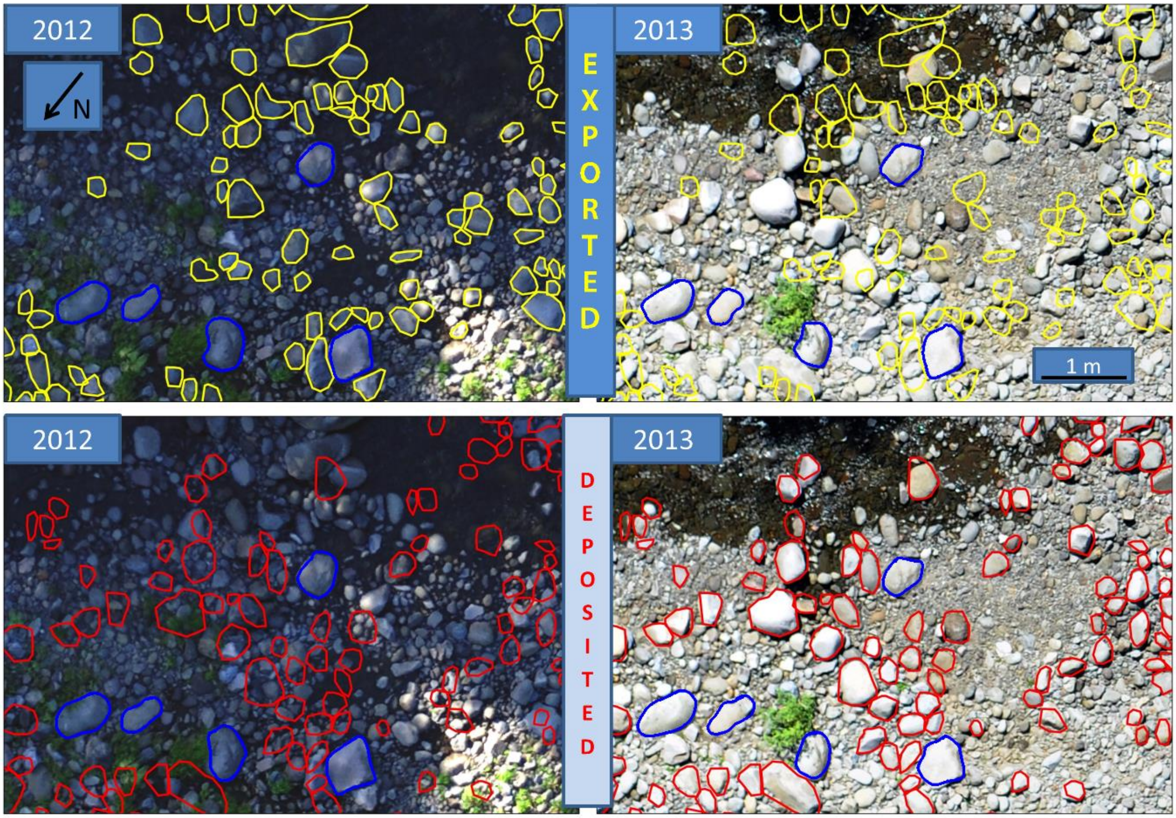

Figure 3: ~~Example of surface change~~Comparison between the surface of the bar in March 2012 (left) and June 2013 (right). The upper pictures show the boulders that ~~were exported~~moved between 2012 ~~to~~and 2013. The lower pictures show the boulders that were deposited during the same period. Some boulders, outlined in blue, visible in 2012 are still there in 2013.~~ These static boulders belong to an indurated basal layer, or belong to the active layer and will be eventually exported.~~

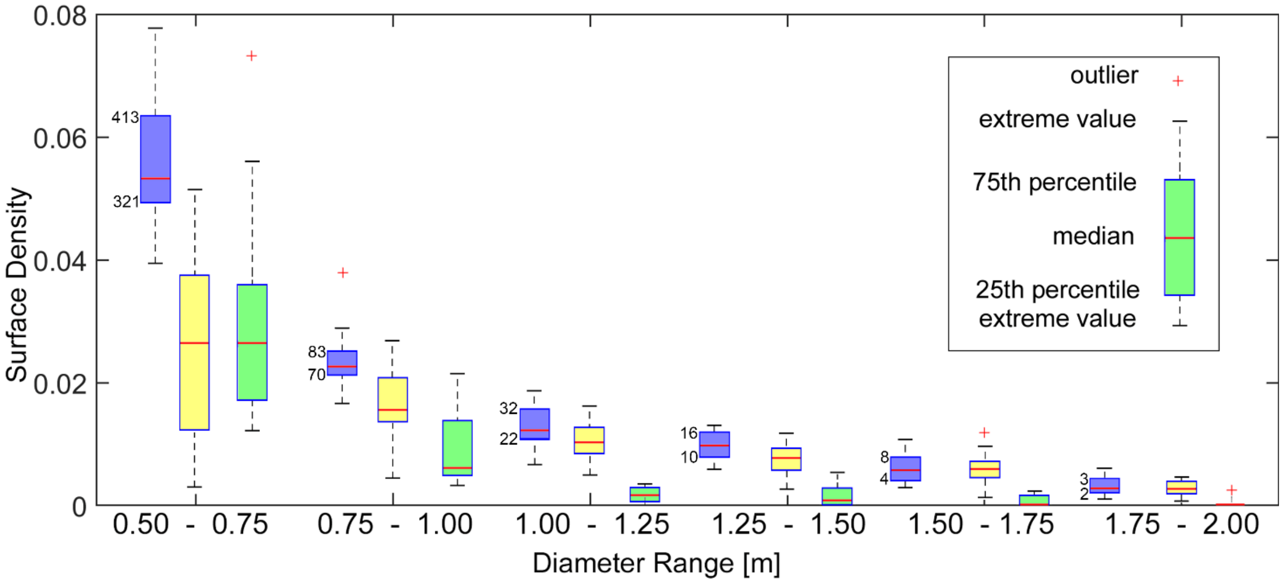

Figure 4: a)4a: Box plot of the surface boulder density (Eq. (1) on the bar as a function of the boulder diameter computed for the 8 yearswhole duration of our datasetsurvey. Blue: total number of boulders; green: freshly deposited boulders; yellow: boulders that were already in place during the preceding campaign of observation b) Surface density of exported, imported and total boulder population. The balance is almost at equilibrium, except from 2013 to 2014, during which years more sediment was exported than deposited. The cumulated surface of boulders decreased during 2012 and 2013. Data from 2010 have been obtain from a preliminary campaign.

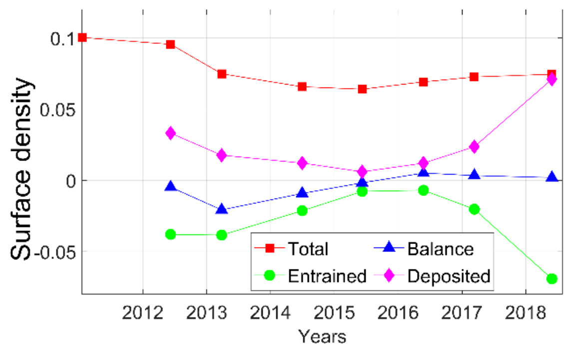

Figure 4b: b) Surface density of entrained, deposited and total boulder population Data from 2010 have been obtained from a preliminary campaign.

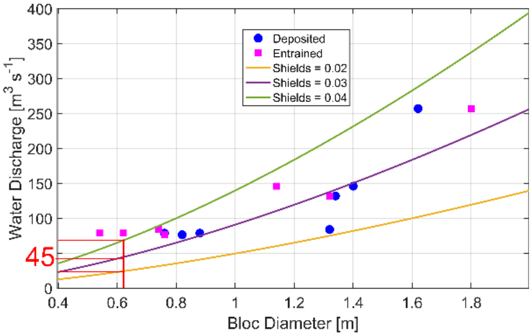

Figure 5: Maximum discharge recorded at the gauge station as a function of the size of the largest transported boulders from 2011 to 2018. The ~~red curve represents~~curves represent the theoretical relation between water discharge and the maximum diameter of the exported or deposited boulders given by Eq. (2) (Appendix 1~~).~~) for 3 values of Shields stress. The threshold discharge for boulders with a diameter of 0.625 m ~~(center of D_1) can be estimated at about 45~~ranges from 24 to 69 $m^3 s^{-1}$ According to the Shields stress. The parameters used for the theoretical estimation of the flow threshold are: Darcy-Weisbach friction coefficient C_f=0.1, critical Shield number Θ_c= 0.02-0.04, width of river, W=30 m, $\Delta\rho$ the density difference between grains and water 1900 kg m^{-3}.

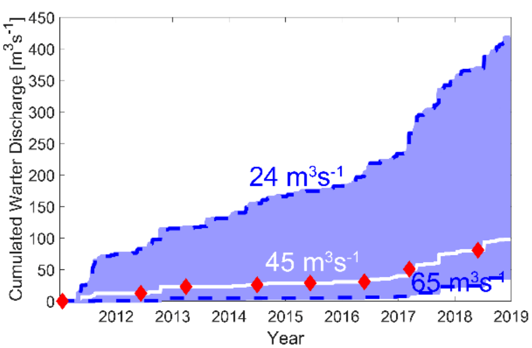

Figure 6: ~~Cumulative duration~~Duration of water discharge between ~~30~~25 and ~~55~~64 m^3s^{-1}. The white line represents a water discharge of 45 m^3s^{-1}. ~~The transport~~Transport is possible only a few hours each year, even during a hurricane year such as 2017. From 2014 to 2016, the transport time was less than 5 hours per year~~.~~ for a threshold of 45 m^3s^{-1}. The red diamonds indicate drone campaigns.

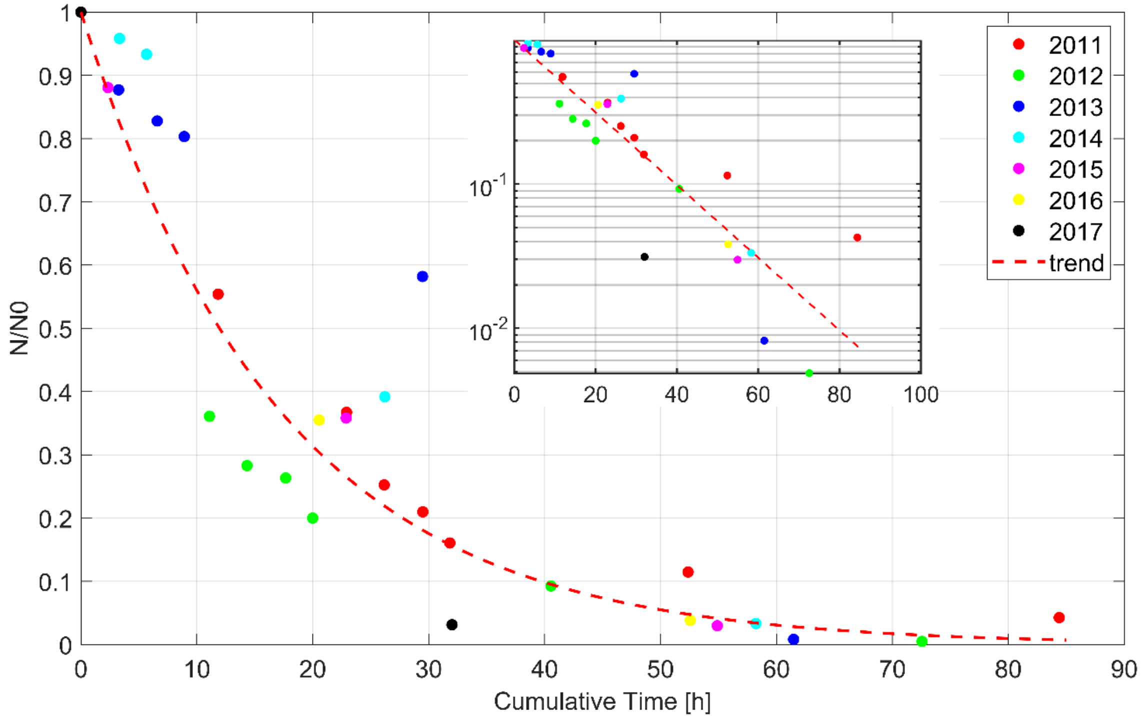

Figure 7: ~~a)~~ Evolution of the ~~normalized~~ number of boulders deposited on the bar between each campaign, and gradually entrained later. The horizontal axis is the transport time for a discharge threshold of 45 $m^3 h^{-1}$. The red curve is the best fit of Eq. 3 ~~that is an (~~exponential decay~~)~~ with a residence time of 17h (half-life of 12 h). ~~That means that the boulders stay on average 17 hours on the bar and that half of the boulders are exported after 12 hours of transport time. B) The inset represents the~~Inset: same data in a semi-logarithmic scale.