Continuous Monitoring of Suspended Load in Rivers under Torrential Hydrological Regime

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Abstract

We report a new methodology for long term sediment transport surveys under extreme conditions. Our approach relies on the use of an instrument developed and tested during a 1.5 years field survey performed from June 2008 to January 2010 on the Capesterre river located on Basse-Terre island (Guadeloupe archipelago, Lesser Antilles Arc). The methodology is based on the use of a LISST-25X sensor and performs real-time in-situ measurements of the water level together with the volume concentration and the average grain size of suspended silts and sand particles with a time step adapted to the state of the river, spanning from one measurement per hour at low flow to one measurement every 2 minutes during a flood. An automatic water sampler installed on the same site is used for the chemical analysis of the suspended sediments.

Keywords: suspended load transport, long term surveys, extreme conditions

1. Introduction

Sediment transport at the surface of the Earth is not a continuous process. The complex geometry of reliefs (fractal organisation of the drainage network and heterogeneous morphology of the slopes), the existence of critical shear stress for sediment entrainment and the stochastic nature of environmental forcing (precipitation, bioturbation, ...) produce sediment transport rates which fluctuate over a wide range of time scales. In particular, recent works have underlined that the flux of material exported outside of a watershed is dramatically increased during extreme climatic events, such as storms, tropical cyclones and hurricanes [2, 3, 6]. Indeed the exceptionally high rainfall rates reached during these events trigger runoff and landsliding which destabilize slopes and accumulate a significant amount of sediments in flooded rivers [5, 7]. This observation raises the question of the control that extreme climatic events might exert on the denudation rate and the morphology of watersheds.

Addressing these questions requires continuous, long term sediment transport datasets based on methodologies able to capture sediment transport even under extreme conditions. In this paper, we present an instrument capable of measuring in-situ both the water level and the concentration of suspended matter in rivers with a time step going from one measurement every hour at low flow to one measurement every 2 minutes during a flood. The instrument is based on the use of a LISST-25X optical sensor developed by Sequoia Scientific, Inc. LISST-25X was included in a complex hydraulic and electronic system controlled by a datalogger and thus became a stand-alone instrument capable of 1) performing long surveys with a minimum human intervention and 2) acquiring data even under extreme climatic events. This instrument was developed and tested during a 1.5 years field survey performed from June 2008 to January 2010 on the Capesterre river located on Basse-Terre island (Guadeloupe archipelago, Lesser Antilles Arc).

2. Description of the field site : the Capesterre river

The Capesterre river is located on Basse-Terre, a volcanic island belonging to the archipelago of Guadeloupe located in the lesser Antilles arc. It drains a watershed of area 37.3 km^2 located along the windward side of the active Soufrière volcano (Figure 1a). Its length is 18.6 km and its bed elevation varies from 1300 m at its upmost

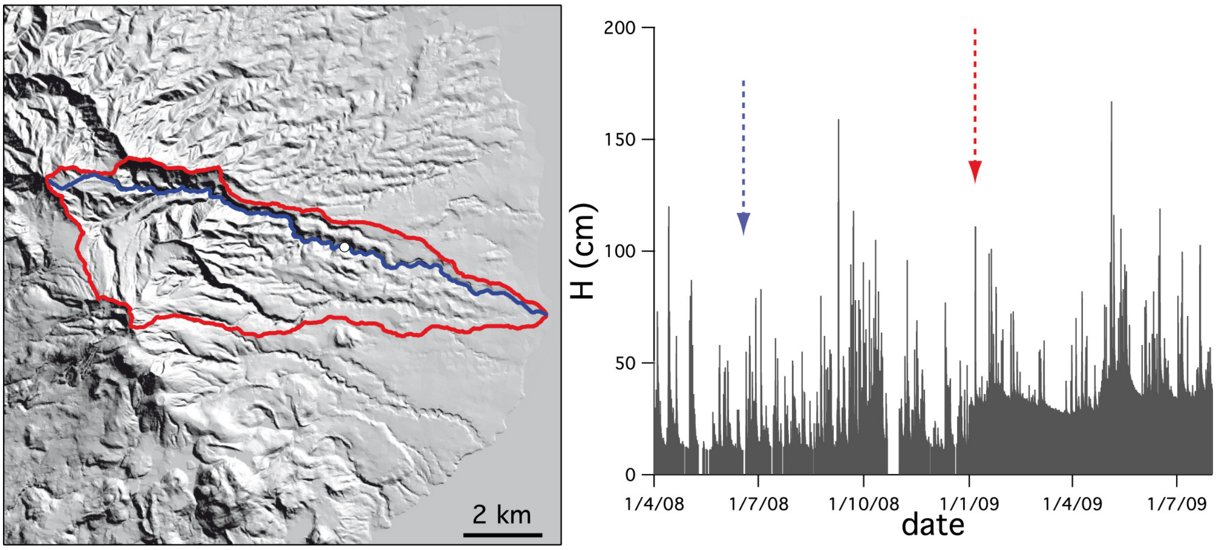

Figure 1: (a) Topographic map of the Capesterre watershed. The frontiers of the watershed and the course of the Capesterre river are plotted in red and respectively blue. (b) Variations of the water flow depth in the Capesterre river between April 2008 and August 2009 (data by courtesy of the Direction Regionale de l'Environnement). Blue arrow indicates the moment where the instrument was installed on the river bank and red arrow the flood described in section 4.

stream to 0 m at the Capesterre village where it reaches the sea. Capesterre was chosen because of its accessibility and because its flow rate is monitored by the Direction Regionale de l'Environnement (DIREN) with a data base covering more than 10 years. Capesterre watershed, mainly composed of lava and pyroclastic flows aged from 600 to 400 ky [8], is characterized by rather thin soils, typically ranging from 0.5 to 2 meters. Capesterre is a bedrock river partially covered by a thin alluvial cover which thickness can increase locally likely due to overwhelming sediment supply from adjacent hillslope, gullies or tributaries. Close to the sea, slopes become gentler and the river bed undergoes a bedrock to alluvial transition. Sampling of sediment beds on 5 sites located at regular intervals along the river course show that the median diameter is comprised between 30 and 250*mm* and reveals the presence of numberous blocks of metric size. The sand fraction is very small (less than 0.2%) except in the immediate vicinity of the sea.

Climate is tropical with high temperatures ($24 - 28°$) and an average annual precipitation rate of about 5200 mm/y. The hydrologic regime is torrential : flow rate is characterized by abrupt variations due to tropical storms and hurricanes particularly frequent during the rainy season from June to January (see Figure 1b).

The largest flood observed during our survey which spanned from June 2008 to January 2010 is illustrated by the inset of Figure 1b. During this flood, the water level in the river increased from 20 cm, corresponding to a flow rate of $1.5\,m^3.s^{-1}$, to 100 cm, corresponding to a flow rate of $42\,m^3.s^{-1}$, within less than 20 min. It took 2 more hours to reach a level of 160 cm, corresponding to a flow rate of $111\,m^3.s^{-1}$.

3. Suspended load monitoring

The method developed to monitor the suspended load in rivers reposes on an LISST-25X (Laser In-Situ Scattering and Transmissometry) sensor developed by Sequoia Scientific, Inc. The theory behind this optical sensor is based on Mie theory of light scattering assuming spherical particles. This instrument determines the volumetric concentration of suspended particles in two size classes (1.25-63 and 63-250 μm) from their characteristic multi-angle forward scattering of a red laser beam. The LISST-25X also measures the Sauter mean diameter (the ratio of total volume to total area of particles) which can be used as a proxy for the mean grain size. LISST-25X operates in a volumetric concentration range going typically from 10^{-2} to 10^{2} ppm, corresponding to massic concentration varying between 10^{-4} and $1\,g/l$. This range varies linearly with the grain size. Higher concentrations can be measured by reducing the optical path of the sensor. Details about this sensor which marks a departure from the simplistic light-source-detector technology employed in previous optical sediment sensors, like turbidimeters, are described by Agrawal and Pottsmith [1].

Important errors can be caused by out of range particles and by particles whose shape is very irregular, far from spherical. Since all shapes other than spheres have a larger surface to volume ratio than spheres, non-spherical particle concentrations will in general be overestimated. A few details about the calibration procedure performed in the lab is given in section 3.1.

LISST-25X is designed to be used by an operator during rather short field survey. After a series of field tests performed in the Capesterre river in 2007, it became obvious that the instrument had to be included in a more complex hydraulic and electronic system controlled by a data logger in order to become a stand-alone instrument capable of 1) performing long surveys with a minimum human intervention and 2) acquiring data even under extreme climatic events. The resulting instrument designed to answer these constraints is discussed bellow (section 3.2).

3.1. Calibration

LISST-25X necessitates two kinds of calibration procedure : 1) The signal recorded by the optical sensor is affected by the state of optical surfaces of the measurement cell. The background scatter data (meaning the "zero" level of the instrument) have to be acquired and saved using clean water. This "zero" level is subtracted from the measured signal so that only the scattering signal from the particles in the water is used for calculating the effective concentration and mean size. It has to be done regularly while doing measurements in the field. 2) Particles transported by rivers have an irregular shape. A calibration is required to account for the deviation from the spherical shape. This in done in the lab by testing the LISST-25X sensor on suspensions of various size and concentration using synthetic and natural particles. The samples were glass spheres of different diameters and natural material (sand from Fontainebleau and sediment from Capesterre river bed) sieved in few classes of size. The material was kept in suspension by vigorous mixing. The measured volume concentration given by LISST-25X optical sensor is represented as a function of the "real concentration". The slope of the best linear fit is the calibration constant. If the particle size is within the instrument range of measurement, the calibration constant is identical. For smaller size particles the concentration is overestimated, while for the larger size particles is underestimated. For particles of spherical shape, the slope is constant of an average value 0.6 and the mean size is well estimated within the given range. For sand from Fontainebleau (nearly spherical form) the results are similar to those on glass spheres (calibration constant of 0.6 and well estimated size). The results are completely different for natural sediments coming from the river Capesterre. Concentration seems larger that in all the other cases (calibration constant betwen 0.77 and 1.28), indicating that there might be a large part of particles smaller than 1.25μm and that the particles shape is far from spherical. This second hypothesis was confirmed by examining the particles under the microscope.

3.2. Description of the field adapted instrument

To avoid destruction of the apparatus during flash floods, the suspended sediments sensor cannot be installed directly in the river bed but needs to be placed on a safe place along the banks. The instrument is therefore equipped with a pump. This later is installed in the river and transfers the water from the river into a measurement cell implemented onto the LISST-25X (see Figure 2). In this way, only the pump, which is rather cheap, is exposed to possible destruction during a large flood. The pump needs to be powerful enough to guarantee that both the concentration and the granulometry of the suspended particles transported to the measurement cell are representative of the suspended load in the river. We used a Barwig 12V/50W submersible pump which provides a discharge of 6l/min, enough to keep all the particles suspended in a 10m long and 8mm diameter tube with a 2.5m level difference between the hose and the measurement cell.

The LISST 25 X sensor needs to be regularly cleaned and the background level measured because the optical surfaces can be contaminated by the biological activity or silt deposition. This is achieved by mean of a second pumping device connected to a clean water tank, used to inject clean water into the measurement cell at regular time intervals set by the user (once a day in our case). A first series of injections are performed to clean the measurement cell. Once this is done, the measurement cell is filled with clean water and the LISST zero level given by the background light scattering of the optical surfaces is registered. A water presence sensor (Honeywell) is used to prevent cleaning and background level measurement if the clean water tank is empty.

Suspended material	Slope	SMD (μm)
Samples within 1.25-250 µm range		
Glass beads 0-50	0.62	54
Glass beads 50-105	0.57	95
Glass beads 70-110	0.65	159
Glass beads 100-200	0.66	272
Glass beads 200-300	0.61	294
Plastic particles 160-250	0.61	157
Sand Fontainbleau 40-250	0.60	218
Sediments Capesterre 40-160	0.77	130
Sediments Capesterre 160-250	0.78	203
Samples containing particles < 1.25 µm		
Talcum	4.15	11
Sediments Capesterre 0-40	1.28	16
Sediments Capesterre 0-250	0.87	90
Samples containing particles > 250 µm		
Glass beads 300-400	0.37	357
Plastic particles 160-500	0.20	126

Table 1: Calibration results (slope and mean size) for a series of suspended sediments measured in the lab.

Another very important measurement problem is related to air bubbles. Bubbles are difficult to avoid ; they come from the gases dissolved into the water or produced by micro-organisms by respiration. The simplest way to get rid of bubbles attached to the optical windows is to completely empty the cell before the measurement by means of a solenoid valve. Then the cell is filled by a sequence of several pumping that allows the bubbles to accumulate at the highest point of the cell and than to be chased by the following pumping period. Then follows a long pumping period by the end of which the measurement is done.

To increase the energetic autonomy of the instrument, we removed the four 9V internal batteries providing the LISST 25 X with energy. Instead, we used an available pin of the LISST cable to connect the instrument to external batteries continuously recharged by solar panels.

In order to save energy and clean water, it is necessary to adapt the measurement time step to the state of the river. This is done by using a hydrostatic level sensor (GEMS Sensors), placed in the river close to the pump hose, which measures the water level every minute. When the water level H exceeds a threshold value H_{start} or if the water level is increasing with a slope larger than a value S, a flood is detected and the measurement frequency is set to a high value, F_{flood} which can reach up to 1 measurement every 2 minutes. This measurement frequency is conserved until H falls below a value H_{stop}. H_{start} and H_{stop} are set by the user and are not necessary equal. In between the floods, the measurement frequency is set to a low value F_{low} chosen by the user. During our field survey on the Capesterre river, we choose $H_{\text{start}} = 50cm$, $H_{\text{stop}} = 40cm$, S= 1cm/min, F_{flood} = 1 measurement every 2 minutes and F_{low} = 1 measurement every hour.

The two pumping devices, the cleaning water circuit, the pressure sensor and the LISST 25X are controlled by a data logger which also stores the data. The data logger is based on a Persistor CF2 that incorporates elaborate control and data logging capabilities into a compact and very low-power module. A standard CompactFlash header is built onto the CF2. The memory card contains a DOS like operating systems allowing to execute a datalogging program that can be loaded from the computer through the serial interface. The datalogger controls the LISST-25X instrument through a receive and transmit RS232 channel. It also controls a relay card that supplies power to the two pumps and the solenoid valve. The signals from the two sensors are connected to two 12 bit AD input channels. Data files (containing water level, size and concentration of the particles) together with log files (containing information about the settings and the functioning of the instrument) are regularly saved on the compact flash disk.

The instrument autonomy is limited mainly by the clean water tank capacity. In our case, the cleaning and

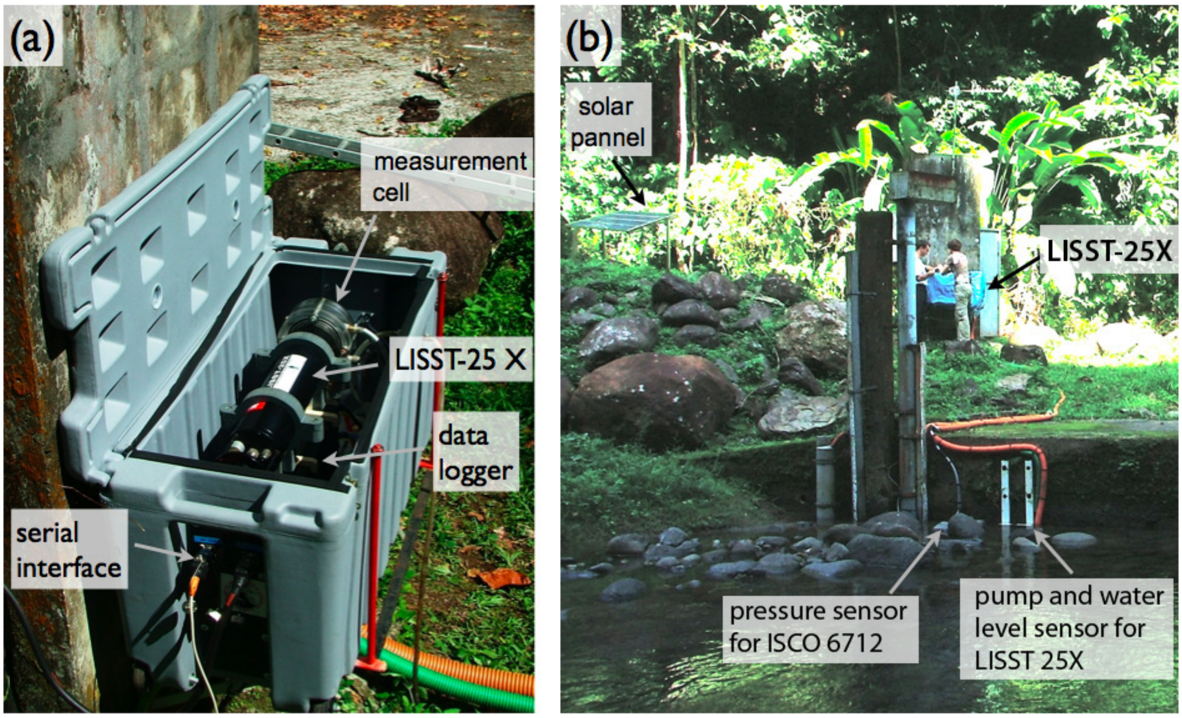

Figure 2: (a) Picture of the field adapted instrument showing the LISST-25 X and the measurement cell. (b) Image of the field test site on the Capesterre river. The sensor and the data logger are located at about 8 meters away from and 2 meter above (at low flow) the river bed while the pump is submersed into the stream.

background procedure consumes 1.6 l, meaning that for a 60 l tank, the instrument has an autonomy of about a month. Once in a month, a maintenance operation is required. It consists in collecting the data, refilling the clean water tank and checking all the components according to a check list (LISST status, pumps and relays).

4. Results

The instrument was installed along the bank of the Capesterre river in June 2008. During that period, it continuously recorded the water depth and the suspended load concentration and granulometry, except for a hole between September 19^{th} and November 4^{th} 2008 due to a failure of the solar panel. Several flash floods occurred during our survey. Although none of them was high enough to lead to important changes of the river bed, they allow us to illustrate the interest of our methodology.

Figure 3 shows data acquired by the instrument during a typical flash flood that occurred on January 6th 2009. Before the flood, the water level in the river was equal to 12 cm, corresponding to a flow rate of about $1m^3s^{-1}$. At around 6 am GMT (2 am, Guadeloupe time), the water level started to rise thus triggering an increase of the acquisition frequency to 1 measurement every 2 minutes. The water level reached a first peak at $H = 83cm$ (about $28m^3s^{-1}$) after almost two hours. After a temporary decrease, the water level rapidly rise again until it reached a second peak at $H = 110cm$ ($50m^3s^{-1}$) around noon. After this second peak, the water level slowly decreased back to normal. The concentration of both silts (grain size in the range 2.5-63 μm) and sand (grain size in the range 63-250 μm) particles, initially equal to zero, started to increase simultaneously with the water level. Their overall evolution reflects that of the water level with some interesting differences. Interestingly, the first peak of suspended load concentration was reached about 40 minutes in advance of the first water level peak, whereas the second peak of suspended load concentration was reached about 10 minutes in delay of the second water level peak.

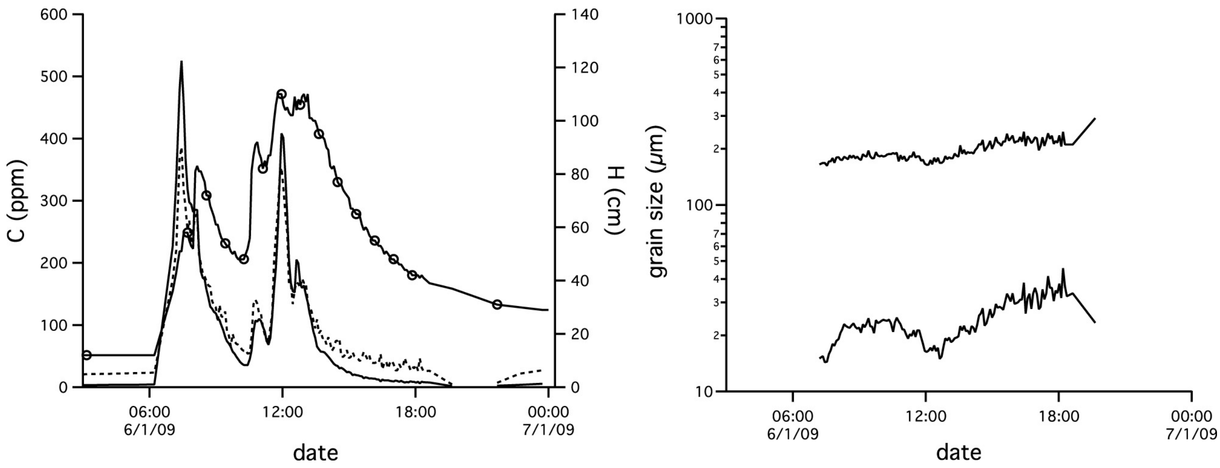

FIGURE 3: Data acquired during a flash flood on January 6th 2009. (a) Water flow depth (line with circles), volumetric concentration of suspended silt (solid line) and sand (dotted line) as a function of time ; (b) Average grain size of silt and sand particles as a function of time.

This observation points out the fact that the suspended load concentration is not a simple and direct function of the flow depth in the river. This is actually best evidenced by the plot of concentration versus water depth shown on Figure 4 which shows an hysteretic behavior. This hysteretic behavior cannot be attributed to a change of grain size. Indeed, as shown on Figure 3 b, the average diameter of the silt and sand particles remained almost constant during the flood. As illustrated by this example, the instrument enables the observation of the suspended load properties with a temporal resolution never reached before. The data acquired are thus likely to lead to new insights on the dynamics of sediment transport. Their detailed analysis goes beyond the scope of the present paper.

5. Discussion and conclusion

We have reported a methodology to estimate the impact of extreme events on sediment transport in rivers. Our approach relies on an instrument developed and tested during a 1.5 years field survey performed from June 2008 to January 2010 on the Capesterre river located on Basse-Terre island (Guadeloupe archipelago, Lesser Antilles Arc). The instrument performs real-time in-situ measurements of the water level together with the concentration and the average grain size of suspended silts and sand particles.

The instrument has several limitations. First of all, the methodology is based on the use of a LISST-25X which operates in a volumetric concentration range going typically up to 10^2 *ppm*, corresponding to mass concentration of

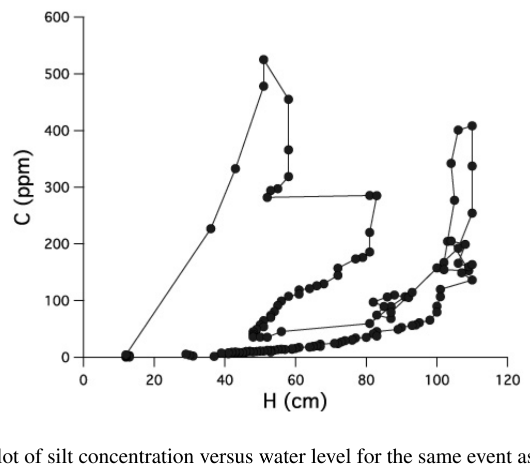

FIGURE 4: Plot of silt concentration versus water level for the same event as on Figure 3.

the order of a few g/l. This maximum concentration was never exceeded during our survey in Guadeloupe. However several authors have documented floods with suspended load concentrations reaching up to 40 g/l, far above the limit of the LISST-25X [4]. To overcome that limit, Sequoia Inc. has developed a new apparatus, called the LISST-INFINITE, which uses an automated dilution system designed to extend the high end of sediment concentration measured with the LISST series instruments up to 500 g/l. Similarly, the use of a LISST-100 instead of a LISST-25X allows one to extend the resolution of the size distribution of suspended sediment from 2 to 32 logarithmically spaced size classes. This is done by the new instrument developed by Sequoia Inc : LISST-Streamside that we are currently testing in Guadeloupe.

Another limit in terms of sediment flux monitoring comes from the fact that LISST-25X cannot determine wether the suspended particles are terrigenic or biogenic. As a result, the measured concentration cannot be directly used to compute a sediment flux. Knowing that the density of terrigenic particles is 2.7 and of biogenic particles nearly 1, the sediment mass flux is overestimated. To overcome that difficulty, we used an automatic water sampler (ISCO 6712) installed on the same site. This sampler is connected to a pressure sensor triggering acquisition (indicated by an arrow on Figure 2b. When a flood was detected, this instrument collected water with a rate of typically 1 sampling every 15 minutes and the acquisition is limited to 24 samples. The filtering and chemical analysis of the samples collected revealed that organic matter represented in average about 23% of the mass of suspended particles, giving a correction factor for mass concentration of about 40%.

The sources of errors for mass concentration are inherent to this type of measurement, based on light diffraction. On one hand they are related to the presence of out of range particles and of particles of very irregular shape and on the other hand to the uncertainty on density. Calibration and complementary chemical analysis of the suspended sediments can help to estimate the error bars.

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