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Title: Uncertainty in the evaluation of sediment yield from badland areas: suspended sediment transport estimated in the Araguás catchment (central Spanish Pyrenees)

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Keywords: suspended sediment transport; sediment concentration; turbidity; grain size; uncertainty; badlands

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Abstract: Badlands are important in terms of sediment yield, particularly in mountain areas having subhumid and humid climatic conditions. Various studies concerning erosion and hydrological processes have demonstrated that suspended sediment transport is probably the main process in sediment export from badland areas. In the Araguás catchment (central Pyrenees) there is a statistically significant positive linear relationship between maximum discharge and the maximum suspended sediment concentration (SSC). The high frequency of hyper-concentrated fluxes of SSC (> 500 g l-1) recorded at two gauging stations close to badland areas in the Pyrenees (Araguás) and the Alps (Draix) indicates that these fluxes are not uncommon, and suggests that they may transport relatively large suspended particles, especially during extreme floods. In a study involving sampling during two moderate floods (August 2006 and February 2007) in the Araguás catchment it was observed that the mean suspended sediment particle size was significantly greater during the highest SSC conditions. The results showed the great heterogeneity of particle sizes that can affect suspended sediment transport, which is usually estimated from concentration determined from turbidity values obtained using infrared devices and associated with the corresponding discharge value. Infrared turbidimeters have problems in detecting particles with a diameter (D) > 0.1 mm, although discharge can be evaluated with relative high accuracy.

The combination of these factors suggests that the evaluation of sediment yield from badland areas using turbidity values involves significant uncertainty. If most suspended sediment is transported during moderate-high floods, which carry large quantities of suspended particles having D > 0.1 mm, then the sediment yield will be underestimated. The uncertainty can be calculated by determining the percentage and mean diameter of particles not detected, and the specific weight of the material. However, the uncertainty is not linear because of the exponential relationship between increasing diameter and the volume/mass, and consequently the error will increase with the growth in the suspended concentration. In this study the physical factors associated with uncertainty in the estimation of sediment yield were investigated, and quantitative estimates of the errors involved are provided.

12 March 2012

Dear Professor Ad,

First of all, thank you very much for your guidance and advice in our revision of manuscript entitled *"Uncertainty in the evaluation of sediment yield from badland areas: suspended sediment transport estimated in the Araguás catchment (central Spanish Pyrenees)"* (CATENA668) that we submitted to Catena for the special issue "updating the badlands experience".

We would also like to express our gratitude to the anonymous Referee and to Dino Torri for their interest in our manuscript. The referee' reports provided thoughtful comments and suggestions that have served to markedly improve the manuscript.

GENERAL POINTS:

1. The Introduction section has been completed with new references and complementary information about hyperconcentrated flow effects on suspended sediment transport, and its close relationship with badland areas. On the other hand, the objectives have been slightly modified to avoid confusions and clarify this study on badland areas.
2. The methodology was reviewed and some specific aspects (laboratory experiences) have been described with more detail.
3. The sections 4 and 5, "Results and discussion" and "Conclusions" have been completely reviewed and strongly modify, as was suggested by Dino Torri. Through more detailed analyses of the results, adding a new figure (Figure 6), adding references with interesting information and improving the discussion. The calculation of uncertainty rates has been more accuracy; these changes are also reflected on Figure 8.
4. A new figure was added (Section 4; Figure 6) to the paper to explain the relationship between suspended sediment concentrations recorded with a turbidimeter device and with an automatic sampler in a badland area. It was observed that the values are lower with automatic samples.
5. We have updated the references. We have changed when it was possible the references that in the previous submission were in press.

6. We changed the reference style according to Catena guide.

The detailed changes introduced, associated with the suggestions and comments of the referees are:

Reviewer 1. Dino Torri

1. We have changed considerably the “Results and Discussion” section to avoid misunderstandings. Firstly, through a better description of field data used to explain suspended sediment yield from badland areas. Secondly, rewriting the “Analyses of uncertainty in the evaluation of sediment transport” (Figure 8) with a more accuracy description of procedures and a more rigorous discussion. And, finally, including new comments in the Conclusions, which has been adjusted to the information previously provided.
2. The term “turbulence” has been replaced by “agitation”, and we assumed that it is more correct and precise to describe the situation. This term has been mainly used to determine changes in the agitation conditions of the water in a little circular pool during laboratory experiments (Figure 7), so it is not possible to obtain any index to express the turbulence conditions of the flow.
3. The discussion of Figure 8 has been rewritten, with a more detailed description and more exhaustive discussion of all uncertainty factors.

Reviewer 2.

1. The introduction and discussion sections have been completed adding information about hypeconcentrated flow effects on suspended sediment transport in badland areas. This information has been associated with the analysis of uncertainty to estimate SSC in badland areas, which currently show exceptional sediment yield amounts as consequence of frequent hyperconcentrated flow situations. These modifications justify more carefully the aim of this work, analysing the additional difficulties that present the usual methodologies to evaluate SSC in badland areas.
2. The reliability of the use of experimental laboratory data for uncertainty analyses of field evaluations has been discussed and commented (sections 4 and 5). On this way, this study has been defined as a serious thinking about the methodological

difficulties associated to particular scenarios (due to its high suspended sediment availability and the heterogeneity of sediment disposability and transport), and the results are considered only an approach of the magnitude in the uncertainty.

Finally, we remain at the disposal of Professor Ad de Roo and the Referees in terms of making additional changes and improvements to the manuscript. Thank you for your assistance and advice on how to improve our manuscript.

Yours sincerely,

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Highlights

1. Suspended sediment transport has been identified as the main global mechanism of fluvial sediment transport.
2. Field measurements and data collection in terms of suspended sediment are generally difficult tasks.
3. The evaluation of sediment yield from badland areas using turbidity values involves significant uncertainty
4. A significant effect of SSC increase on variations in the suspended grain size was observed.
5. Automatic samplers typically show an overestimation of turbidity methods

Uncertainty in the evaluation of sediment yield from badland areas: suspended sediment transport estimated in the Araguás catchment (central Spanish Pyrenees)

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ABSTRACT

Badlands are important in terms of sediment yield, particularly in mountain areas having subhumid and humid climatic conditions. Various studies concerning erosion and hydrological processes have demonstrated that suspended sediment transport is probably the main process in sediment export from badland areas. In the Araguás catchment (central Pyrenees) there is a statistically significant positive linear relationship between maximum discharge and the maximum suspended sediment concentration (SSC). The high frequency of hyper-concentrated fluxes of SSC (> 500 g l^{-1}) recorded at two gauging stations close to badland areas in the Pyrenees (Araguás) and the Alps (Draix) indicates that these fluxes are not uncommon, and suggests that they may transport relatively large suspended particles, especially during extreme floods. In a study involving sampling during two moderate floods (August 2006 and February 2007) in the Araguás catchment it was observed that the mean suspended sediment particle size was significantly greater during the highest SSC conditions. The results showed the great heterogeneity of particle sizes that can affect suspended sediment transport, which is usually estimated from concentration determined from turbidity values obtained using infrared devices and associated with the corresponding discharge value. Infrared turbidimeters have problems in detecting particles with a diameter (D) > 0.1 mm, although discharge can be evaluated with relative high accuracy.

The combination of these factors suggests that the evaluation of sediment yield from badland areas using turbidity values involves significant uncertainty. If most suspended sediment is transported during moderate–high floods, which carry large quantities of suspended particles having D > 0.1 mm, then the sediment yield will be underestimated. The uncertainty can be calculated by determining the percentage and mean diameter of particles not detected, and the specific weight of the material. However, the uncertainty is not linear because of the exponential relationship between increasing diameter and the volume/mass, and consequently the error will increase with the growth in the suspended concentration. In this study the physical factors associated with uncertainty in the estimation of sediment yield were investigated, and quantitative estimates of the errors involved are provided.

Key words: suspended sediment transport, sediment concentration, turbidity, grain size, uncertainty, badlands

1. INTRODUCTION

Hydrological studies have demonstrated that fluvial sediment transport is dominated by suspended material, which can exceed 90% of total transport (Newson, 1986; Webb et al., 1995) and is generally substantially greater than the quantity of dissolved material transported (Walling and Webb, 1986). Large storms and floods carry most of the sediment loads annually (Olive and Rieger, 1984; Edwards, 1987; Jansson, 1988; Evans et al., 1997), as has been shown to occur in several Mediterranean environments (Romero et al., 1988; Woodward, 1995; Wainwright, 1996; Gallart et al., 2005; García-Ruiz et al., 2008).

This process can be extensive in badland areas because of their particular geomorphological dynamics (Yair et al., 1980; Bryan and Yair, 1982; Cerdà and Navarro, 1997; Torri et al., 2000; Cantón et al., 2001; Gallart et al., 2002). Thus, studies have shown the most intense weathering and erosion processes occur in badlands in humid mountain environments (Antoine et al., 1995; Regüés et al., 2000a; Decroix and Mathys, 2003; Regüés and Gallart, 2004; Nadal-Romero et al., 2007; Nadal-Romero and Regüés, 2009), which are reflected in large sediment yields (Regüés et al., 2000b; Mathys et al., 2005; Nadal-Romero et al., 2008a, 2008b) and irregular temporal trends in sediment export (Regüés et al., 2000b; Nadal-Romero and Regüés, 2010). This is a consequence of the particular features of the hydrological response of badland areas, where runoff generation is dominated by Hortonian mechanisms that favor the generation of flash floods associated with intense precipitation events (Gallart et al., 2002; Nadal-Romero et al., 2008c).

For fluvial environments there is a poor relationship between the suspended sediment concentration (SSC) and discharge (Olive and Riege, 1985; Zabaleta et al., 2007; López-Tarazón et al., 2012), which can be something better in semi-arid environments (Alexandrov et al., 2003). But for badland areas a strong relationship between SSC and peak flow (Q_{max}) has been observed (Regüés et al., 2000b; Nadal-Romero et al., 2008b), with estimates of the SSC reaching occasionally values up to 500 $g \cdot l^{-1}$ (Mathys et al., 2005; Nadal-Romero and Regüés, 2010). These hyper-concentrated fluxes (Costa, 1988) probably include suspended particles exceeding medium-coarse sand in size, because the particular properties associated with these fluxes increase its fluid density and viscosity, while sediment settling and flow velocity decrease (Heesel, 2006) and in some studies it has been observed a direct positive relationship between concentration increases and transport capacity (Wan and Wang, 1994; Xu, 1999a) and with suspended sediment size (Frostick et al., 1983; Long and Qian, 1986; Reid and Frostick, 1987; Xu, 1999b); this is particularly the case during the biggest floods, because of the relationship between an increase in the diameter of particles and increasing discharge (Soler et al., 2003; Soler and Gallart, 2006).

The SSC can be evaluated by sampling during floods and/or by continuous recording of turbidity measurements. Regular but infrequent sampling (e.g. weekly and monthly) may lose major events (Dickinson, 1982; Foster et al., 1992; Gippel, 1995; Webb et al., 1995), and automatic samplers that are able to operate during floods are limited in terms of their ability to sample particles up to medium sand (Soler et al., 2006). These factors can result in underestimates of suspended sediment transport. This limitation can be resolved through continuous recording turbidity measurements, which provide a relationship with suspended sediment concentrations (SSC), and are commonly obtained using infrared devices. Though, these estimations are subjected to problems associated with the physical characteristics of sediment (Gippel, 1995), specifically the grain size (Cliffort et al., 1995). This occurs because the specific turbidity (the turbidity independent of particle concentration) is at a maximum where the particle radius nears the wavelength of the impinging light (Vanous et al., 1982); thus, the greater the average particle size the lower the estimated turbidity of the water. This effect was investigated by Gibbs (1974), who reported that particles 0.5–1 μm can attenuate light up to 7.5-fold more than particles 5–10 μm in size, while Campbell and Spinrad (1987) showed insignificant attenuation of turbidity by particles > 100 μm in diameter. A consequence is the underestimation of the SSC in high concentration situations if large particles are suspended in the flow.

In several studies relatively good estimates of erosion from turbidity measurements at low sediment concentrations have been obtained (Van Bueren, 1984; Finlayson, 1985), but these have generally been associated with small storm events involving a short range of sediment concentrations and long time intervals. Turbidity and SSC relationships based on low sediment concentrations or infrequent storm monitoring may result in significant errors (Sun et al., 2001).

In this study, uncertainty in estimates of suspended sediment yield in badland areas associated with limitations in methodologies and probes was analyzed as the main objective. Sediment export was assessed in the Araguás experimental catchment (central Spanish Pyrenees) characterized by the dominant presence of a badland system in the lower sector. The uncertainty in suspended sediment yield was determined using empirical and experimental data from:

1. the textural distribution of sediment samples collected in traps located above the stream bed during two floods with different magnitudes of discharge and SSC;
2. the ratio between SSC values measured in samples obtained using an automatic sampler (ISCO 3700), and estimated from continuous records using a back-scattering turbidimeter (Hendress+Hauser CUS41). These analyses were undertaken at simultaneous values from the same time and discharge conditions during the event;
3. the results of previous experiments assessing the relationships between increased particle size and turbidity, and the effect of agitation power increase on the SSC and its grain size distribution.

2. STUDY AREA

The Inner Depression is an east–west orientated morphostructural landscape located in the central Pyrenees (Fig. 1). It is drained by the Aragón and Gállego rivers, which are tributaries from the north of the Ebro River. The altitude of the Depression ranges from 500 to 1200 m a.s.l., and the bedrock is mainly composed of Eocene marls with occasional sandstone layers. This area is characterized by a dense network of badlands of various sizes, which occupy a total area of 15 km^2 (3.4% of the total surface; Nadal-Romero et al., 2007). The landscape has been markedly influenced in recent centuries by deforestation, frequent wildfires, overgrazing and cultivation on steep slopes (Lasanta et al., 2006). *Pinus sylvestris* forest cover north-facing slopes, while south-facing slopes are affected by abandoned fields and reforested *Pinus nigra* plantations. Terraces and pediments are occupied by cereal crops or natural regrowth of sub-Mediterranean shrubs (*Genista scorpius, Buxus sempervirens and Rosa gr. canina*) following rural abandonment.

The Araguás catchment (Fig. 2) drains the Lubierre River, which is a tributary of the Aragón River. It is a small catchment (0.45 km^2) located at a moderate altitude (780–1105 m a.s.l.). The bedrock in the lower part of the catchment consists of massive Eocene marls with some decimeter-scale sandy layers, while the substratum in the upper part of the catchment comprises Eocene flysch rocks (turbidite deposits). Three areas with differing land cover types can be differentiated within the Araguás catchment: (i) the headwater is a steeply sloped terraced hillside, which since field abandonment in the 1960s has been planted with *Pinus nigra* forest and subject to spontaneous regrowth of shrubs. This area represents about the 30% of the catchment area (13.5 ha); (ii) the central area has gentler slopes that are dominated by meadows on abandoned terraces, which have been progressively colonized by grasslands and shrubs. It is the largest area (approximately 20 ha; 44% of the total catchment surface), and is currently used as pasture for horses and sheep; (iii) the lower area (approximately 11.5 ha; 26% of the catchment total surface) is characterized by badlands developed over marly substratum. The topography is complex, with very steeply sloping areas and a high density of drainage net. This area is geomorphologically dynamic, with rapid regolith development associated with the intensity and effectiveness of weathering and rainfall–runoff erosion processes. As a consequence, these areas are characterized by high availability of sediments for fluvial export, and large suspended sediment transport.

The climate is considered Sub-Mediterranean because it has the typically marked Mediterranean seasonal differences in temperature and precipitation, but is also substantially influenced by humid winds from the Atlantic Ocean and cooler air from central Europe (Creus, 1983). The average annual precipitation is approximately 800 mm, with two major rainfall periods (autumn and spring), convective storms usually occur in summer, and occasional snowfalls in winter. The average temperature is 10°C (minimum –14°C and maximum > 30°C) but marked daily oscillations of temperature can occur, particularly in summer when ranges of approximately 27°C can occur. The soil temperature and moisture conditions are associated with slope orientation; wetter and cooler conditions occur on slopes in shadow, where freezing cycles frequently occur between late autumn and early spring, while on sun-exposed slopes drought conditions and high temperatures reduce ice formation. These conditions are especially evident in the badlands areas because of the great complexity of the topography and the development of drainage net.

3. MATERIALS AND METHODS

The hydrological and sediment responses of the Araguás experimental catchment were monitored at a gauging station (Fig. 3a), and precipitation data were obtained from three automatic pluviometers located at different altitudes in the catchment. The discharge was obtained from continuous recording (5 min frequency) of water levels using an Ultrasonic Pepper Flux Probe (for large discharges) and a Pressure Keller Probe (for small discharges). The suspended sediment concentration was evaluated using two methods:

1. A turbidity continuous evaluation using a back-scattering Infrared sensor (Hendress+Hauser CUS41); data are obtained every 10 seconds and mean values recorded every 5 minutes intervals.
2. Sampling of water (24 × 0.50 l samples) during flood events using an automatic sampler (ISCO 3700); with a variable frequency depending on the electric pulses emitted from the datalogger, which programmed to act when a threshold of the water level and/or SSC is exceeded, being the minimum interval 10 minutes.

The suspended sediment transport was calculated for short time intervals using the product of the discharge volume and the estimated SSC, obtained from turbidity records that were previously calibrated using fine sediments from the channel. The SSC obtained by direct measurement of water samples was used to obtain the ratio respect the SSC from turbidity, which provide the estimation of uncertainty between both methodologies (automatic sampler and turbidimeter devices).

To assess the transport of large particles (large sand or gravel) in suspension during floods the within-flood suspended sediment grain size distribution was analyzed by installing three sediment traps on the middle of the stream bed close to the gauging station. These consisted of PVC tubes (3 cm diameter) placed to enable sampling of sediment at three water levels (5, 12 and 25 cm from the channel). The traps filled with water and sediment during the flood; the buried side of the tube was covered with a fine metal net to allow sediment retention and water circulation (Fig. 3b).

The relationships between turbidity, grain size and SSC were obtained from Regüés et al. (2002). Their study comprised two simple laboratory experiments involving the use of a small pool equipped with a mechanical agitation system. One experiment investigated the effect of grain size on turbidity, through continuous back-scattering infrared probe turbidity measurements of water containing suspended sediment particles of three homogeneous grain size situations (clay–silt, fine sand and medium sand). The second evaluated the effect of water power agitation increase on the features of suspended particles (concentration and grain size), and involved sampling of suspended sediment composed of heterogeneous particles (ranging from clay to medium sand) under two agitation conditions (250 and 500 r.p.m.).

4. RESULTS AND DISCUSSION

Sediments yield from the Araguás catchment

The analyses of 176 floods recorded at the gauging station of the Araguás experimental catchment (December 2005-June 2010) has been used to quantifying suspended sediment yield from badland areas, throughout the SSC estimations obtained from turbidity continuous records, that provides erosion rates around 50,000 Mg·yr^{-1} with very irregular temporal distribution (Nadal-Romero and Regüés, 2010). Figure 4 shows the percentage of recorded events related to the accumulated suspended sediment yield, precipitation and stormflow, and demonstrate that the greater quantity of sediment yield (90%) and stormflow (75%) are associated with a few number of events (20%), and with a relatively high rainfall volume (45%). While a more detailed study of this process revealed that the correlation between SSC and discharge volume is not significant (Nadal-Romero et al., 2008a), during the driest periods, when runoff is produced only from badlands; however a stronger positive relationship was evident between SSC values and the peak discharge (Nadal-Romero et al., 2008b; Regüés et al., 2009). These results suggest the possibility to explore with more detail the effect of discharge and SSC conditions on grain size features of suspended particles, especially in the area corresponding to the action range of sediment evaluation devices (usually close to the deeper level of the flow).

Characteristics of the suspended sediment transport related to the discharge and SSC conditions

The analyses of suspended sediment grain size distribution related to different flood power and SSC conditions was studied through the sediment collected in the 5-8 cm and 12-15 cm traps (Fig. 5) following two moderate events (unfortunately the trap located at 25-28 cm was destroyed during the first flood). The biggest event, recorded in February 2007 (Q_{max} 347 $l\cdot s^{-1}$ and SSC_{max} 630 $g\cdot l^{-1}$) had ~18 and 6% of particles with diameter (D) > 1 mm, at 5-8 and 12-15 cm flow level respectively, and some gravel particles were found in the traps (D > 10 mm at 12-15 cm, D > 30 mm at 5-8 cm). The smallest flood, in August 2006 (Q_{max} 206 $l\cdot s^{-1}$ and SSC_{max} 145 $g\cdot l^{-1}$) had ~4.3 and 1.5% of particles with D > 1 mm; gravel particles were only found in the 5-8 cm trap, and their size was significantly smaller (D = 10 mm). These results confirm that increasing power of the discharge and SSC can significantly modify the characteristics of suspended particles, and suggests the possibility that gravel will be incorporated in the deeper flow areas, especially if reaching hyperconcentrated conditions. In this case, the increase of ~1.7 fold on discharge and ~4.3 fold on SSC is associated with a significant variation on the percentage of suspended particles up to 1 mm (~4 fold) at the interval 5-15 cm water level of flow. These differences suggest that suspended grain size particles diameter could be strongly affected by discharge and SSC variations, which probably affects largely in the deeper levels of the flow. Wherever, this hypothesis must be corroborated through a specific study. On the other hand, the results agreed with the positive relationship observed between grain size and SSC (Frostick et al., 1983; Long and Qian, 1986; Reid and Frostick, 1987; Xu, 1999b) and also with discharge increase (Lewis, 2003; Soler and Gallart, 2006), suggesting that the relationships between turbidity and SSC can be expected to be much more complex than simple (Old et al., 2003). On this way, in a previous study was noted that for SSC up to 200 $g\cdot l^{-1}$ more sediment can be carried by flows, because the decrease of the settling velocity (Wan and Wang, 1994) that is associated with the increases of the fluid density (Xu, 1999a) and which results in a lower submerged density of the particles. This confirms the great importance and difficulty to obtain correct evaluations of SSC in badland areas, where the quick variability of suspended particle features associated with flow level should have an effect on the placement of evaluation systems (automatic samplers and turbidimeters) with static location. On this way, the limitation of SSC estimation devices was investigated, to evaluate its respective accuracy and their relationships with the factors related with SSC variations.

Differences between suspended sediment concentration evaluations by turbidity and automatic water samplers

For 176 floods the maximum SSC estimated by turbidity methods was > 100 g·l^{-1} in 34% of the events, and in approximately 15% of the events the maximum value was 500–800 g·l^{-1} (Nadal-Romero et al., 2008a). However, the SSC determined using the automatic samples showed maximum values around 200 g·l^{-1}, which normally reflects lower values respect the values obtained from turbidity estimation (Nadal-Romero, 2011). The comparative analysis of values showed that the typical ratio between the two evaluation methods was 3.07:1 (Fig. 6). This can be explained by the limitations in the suction power of automatic samplers, which probably shows difficulties to pick up the largest sand particles, since 250 μm diameter, and result unable with sand particles up to 500 μm diameter (Soler et al., 2006); together with the lower number of measurements, this result in poorly representative samples of transported particles, with negative consequences on the SSC estimation. This observation is consistent with the underestimation of sediment load associated with the manual sampling estimation (Littlewood, 1992), and especially during important storms and big flood events (Guy, 1965; Olive and Riege, 1988).

Effects of grain size on turbidity and SSC evaluation

Regüés et al. (2002) investigated the effect of grain size variations on water turbidity and sediment concentration. Firstly, measuring the turbidity and SSC produced by particles of different texture: clay–silt (<62 μm), fine sand (62-500 μm) and medium sand (500-1000 μm); and secondly, by studying the effect of increasing water agitation power, to simulate the increase of discharge transport power, on the sediment concentration and suspended grain size distribution. The results of the first experience showed a progressive increase in the slope of the correlation fit as the texture varied from clay–silt to medium sand (Fig. 7a). The lineal relationships between SSC ($g \cdot l^{-1}$) and turbidity (NTU) show the maximum slope rate (2.3:1) between clay-silt (solid line) and medium sand (discontinuous line):

SSC (clay-silt) = 0.359+0.0026*NTU (n: 36, R: 0.95, p-level < 0.0001)

SSC (fine sand) = -0.035+0.0036*NTU (n: 36, R: 0.98; p-level<0.0001)

SSC (medium sand): -0.069+0.0059*NTU (n: 15, R: 0.98, p-level < 0.0001)

This confirmed the minor influence of large particles on turbidity, as reported in previous studies (Campbell and Spinrad, 1987; Cliffort et al., 1995), but also showed the important effect on sediment concentration. However, significant differences in the grain size distribution and SSC (Fig. 7b) of two water samples were evident following an increase in the agitation conditions (250 to 500 r.p.m.) in the experimental pool. These results demonstrated that a relatively small increase in the D_{50} grain size diameter (from 18 to 62 μm) was associated with large variations in the SSC (from 4.9 $g \cdot l^{-1}$ to 33.0 $g \cdot l^{-1}$) with a rate of 6.5:1. In this case these differences can be explained by a quantitative cause, due to the higher number of suspended particles after increasing agitation power, but also by the qualitative effect produced by the high percentage of coarse particles respect to the occurrence of fine particles. This can appear to be the main explanation for the difference in the SSC, taking into account the exponential relationship between the diameter and the mass of spherical particles. But, this result could also be associated with the grain size threshold of 100 µm for growing the attenuation on the detection of particles by turbidity probes (Campbell and Spinrad, 1987). These experimental tests demonstrate the close interactions existing between discharge, particles size and SSC increases, which have a direct effect on the turbidity conditions, considering the observed variation in the particle size distribution related to an increase in discharge (Soler et al., 2003; Soler and Gallart, 2006), and the increase in average size directly related to concentration (Frostick et al., 1983; Long and Qian, 1986; Reid and Frostick, 1987; Xu, 1999b). The combined effect of all these factors can result in considerable errors, probably reaching up to one order of magnitude under hyperconcentrated flow situations, on the evaluation of SSC through turbidity estimations.

Analyses of uncertainty in the evaluation of suspended sediment transport

The uncertainties considered in this study have a major effect on the evaluation of suspended sediment transport. The interactions among variations in the power of the flow, grain size, SSC and turbidity significantly increase the complexity of quantifying suspended sediment export. This is particularly the case for badlands because of their rapid variations in discharge conditions, high sediment yields, and the heterogeneity of sediment available (Nadal-Romero and Regüés, 2010). These uncertainties must be taken into account to considering the sediment rates as an approach of the magnitude, because of the high probability of underestimating SSC as a consequence of previous analyses limitations in turbidity measurements.

Figure 8 shows the annual sediment transport rates calculated from the turbidity records for the Araguás badland areas during the period December 2005 to June 2010 (only for 2006 and 2009 are the entire hydrological year data shown), and includes the corrections obtained from laboratory experiences, which are associated with underestimates produced by turbidity measurement limitations: combining the difference in the linear regression between clay–silt particles and medium sand (Fig. 7a), which produced a ratio of approximately 1:2.3, and the differences in particle size distribution following an increase in the turbulence (Fig. 7b), where the ratio reached 1:6.5. And also, the most improbable but not impossible, overestimation of 3.07:1 obtained between turbidity methods respect the values provided of automatic samples (Fig. 6). The differences in sediment yield can be very substantial, depending on the correction factor applied. The rates of suspended sediment transport estimated for the study period (only for 2006 and 2009 were complete hydrological years) provide transport rates of 68,000 and 18,000 $Mg \cdot km^{-2} \cdot yr^{-1}$, respectively. These values suggest substantial interannual variability in sediment transport. However, the uncertainty involved in the evaluation of the SSC must be considered. The effect of discharge and SSC increase, on variations in the suspended grain size was confirmed empirically in the study area (Fig. 5). In addition, limitations in the methods involved in turbidity and sampling measurement were previously reported (Guy, 1965; Dickinson, 1982; Olive and Riege, 1988; Foster et al., 1992; Littlewood, 1992; Clifford et al., 1995; Gippel, 1995; Webb et al., 1995; Soler et al., 2006). The turbidity method can underestimate the SSC, because the before mentioned negative relationships between turbidity and grain size increase, confirmed by laboratory experiences (Fig. 7a). This effect must be very important considering the significant increases of grain size measured from the samples obtained with-in two floods (Fig. 5), together with the results from laboratory experiments (Fig. 7b).

On the other hand, automatic samplers typically show an underestimation of turbidity methods, because these devices also present significant limitations that probably results in the absence of the biggest particles in the samples. This could result in tenfold error in sediment yield estimation in badland areas, which can be directly related to wide levels of heterogeneity that can reach the suspended sediment grain size. This is a consequence of the hyperconcentrated flow conditions, especially during the biggest floods, which affects fluid properties (Hessel, 2006) and increases its transport capacity (Xu, 1999a).

It must be also taken into account the irregular patterns observed on sediment transport in mountainous rivers and especially in the headwaters areas, defined as “sediment pulses” (Cui and Parker, 2003) with predominance of coarse particles from the stream bed, and especially close to the deeper flow areas. The results of this analysis suggests that the variability in inter-annual rates of suspended sediment transport from badlands could be less than or equal to the uncertainty associated with limitations in the methods (Fig. 8).

The experiments to establish correction factors to address limitations in turbidity measurements were obtained using relatively small particles $\leq 1000\ \mu m$, but it has been observed empirically (Fig. 5) that a medium-sized flood can contain suspended sediment that includes a significant proportion of large particles in the order of $1000\ \mu m$ diameter, which shows a significant increase of about four times (since 4.3 to 18 % at 5-8 high, and since 1.5 to 6 % at 12-15 cm high), that is similar to the differences of SSC (since 145 to 630 $g \cdot l^{-1}$) estimated in both events. Thus, suspended sediment export could be underestimated by a factor between 2.3 (Fig. 7a), from turbidity/SSC method limitations, and a value close to half order of magnitude (Fig. 7b), considering the great effect on SSC of coarse particles. So, this can result in an error growing up to ten-fold if considering the combined effect of both factors. Turbidity is an optical effect, derived from the quantity and dispersion of solid material suspended in water. Many small homogeneously distributed particles increase the turbidity to a much greater extent than a small number of large particles having the same mass, because the specific turbidity is independent of sediment concentration (Vanous et al., 1982). However, large particles produces increases most efficiently the SSC than lower ones. The results of Regüés et al. (2002), illustrated in Figure 7, demonstrate that a relatively small increase in the average particle diameter can produce much greater variations in SSC than in turbidity.

Finally, it must be taken into account that this study has been founded basically on laboratory experimental assumptions, with the support of some field empirical evidences and information. For this reason, it must be careful on the extrapolation of these results to the field data, because the greater complexity of suspended sediment transport processes on field conditions respect the simplicity of laboratory measurements. This involves the heterogeneity of sediment properties, including the variation on grain size produced by fragmentation of sediment particles during transport, the variations of flow power associated with the channel morphology, and with the water level of discharge, including inside the flow, which affects directly on continuous changes on the suspended sediment features and amounts during a single event (Cui and Parker, 2003), which confirms the high complexity involved in the sediment transport process. On this way, the sediment size variations with-in transport process can be excluded in little headwaters catchments (Brummer and Montgomery, 2003) while the effects associated with hyperconcentrated flow conditions and discharge power can largely exceed the laboratory results.

The analyses of methodologies and variables associated with the evaluation of SSC, have demonstrated the difficulties to estimate the sediment yield in an intensely eroded landscape (produced basically by same evaluation methods), but also have provided some approach about the magnitude that can reach the errors. The most important limitation on the estimation of the magnitude of this uncertainty is the own variability, because the relationship with the magnitude of the events is positive, but also depends on grain-size distribution of suspended particles, that shows an exponential relation with SSC.

CONCLUSIONS

The methodologies for the evaluation of stream sediment yield show important limitations, associated with the characteristics of the suspended sediment and its heterogeneous distribution in the flow during the events. This produces important uncertainty on the estimation of SSC that, together with discharge volume, is the most important factor for evaluating suspended sediment transport. These difficulties increase in the studies on badland areas, because the hyperconcentrated flow conditions, that are associated with suspended sediment transport from these landscapes, can affect largely the capacity of transporting suspended particles. The results had provided an idea about the uncertainty of sediment yield rates, which high interannual variability could be probably similar to the magnitude of the error. The estimations of SSC from sampling of turbidity continuous recording show problems and limitations, associated with the continuous variations of transport capacity during the events.

On the other hand, this study has been founded on a combination of laboratory experimental data and field information, for this reason the estimations must be taken carefully, but assuming that field situations probably results in the underestimation of sediment yield rates. The magnitudes of the uncertainty could reach about ten-fold the estimation, but this is only an approach that must be investigated through additional field information.

AKNOWLEDGEMENTS

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Figure captions

Figure 1. Distribution of badlands in the Inner Depression (central Spanish Pyrenees).

Figure 2. Location of the Araguás experimental catchment. Badlands landscapes in the Araguás catchment.

Figure 3. The Araguás gauging station (A) and sediments traps located on the stream bed (B).

Figure 4. Percentage of accumulated suspended sediment transport, storm flow and precipitation in the Araguás catchment in relation to the percentage of the number of events (176 events).

Figure 5. Grain size distribution of suspended sediment particles at two levels in the stream bed, determined from two floods having moderate discharge volumes (Q_{max} 206 $l\cdot s^{-1}$ and 347 $l\cdot s^{-1}$, 18/08/2006 and 09/02/2007 respectively).

Figure 6. Relationship between the SSC estimated by 192 values from water samples (ISCO automatic sampler) and turbidity records.

Figure 7. Influence of particle grain size on the relationship between turbidity and suspended sediment concentration. Figure 7A shows the relationships obtained using a back-scattering probe for three textural classes and NTU turbidity: clay-silt (solid line), fine sand (discontinuous line) and medium sand (dotted line). Figure 7B shows the effect of increasing agitation on grain size distribution and concentration of suspended particles; the red and grey lines shows lower (250 r.p.m.) and higher (500 r.p.m.) agitation power conditions, respectively.

Figure 8. Sediment yield rates for the badland areas of the Araguás catchment (only for 2006 and 2009 hydrological year the data are complete). The different lines show the ranges of uncertainty associated

with the experimental differences obtained in this study, associated with the limitations of SSC evaluation methodologies: estimation through samples and turbidity records (rate 3.07:1), differences between clay-silt and medium sand particles on turbidity (rate 2.3:1) and variations of concentration after increasing agitation power (6.5:1).

Figure 1

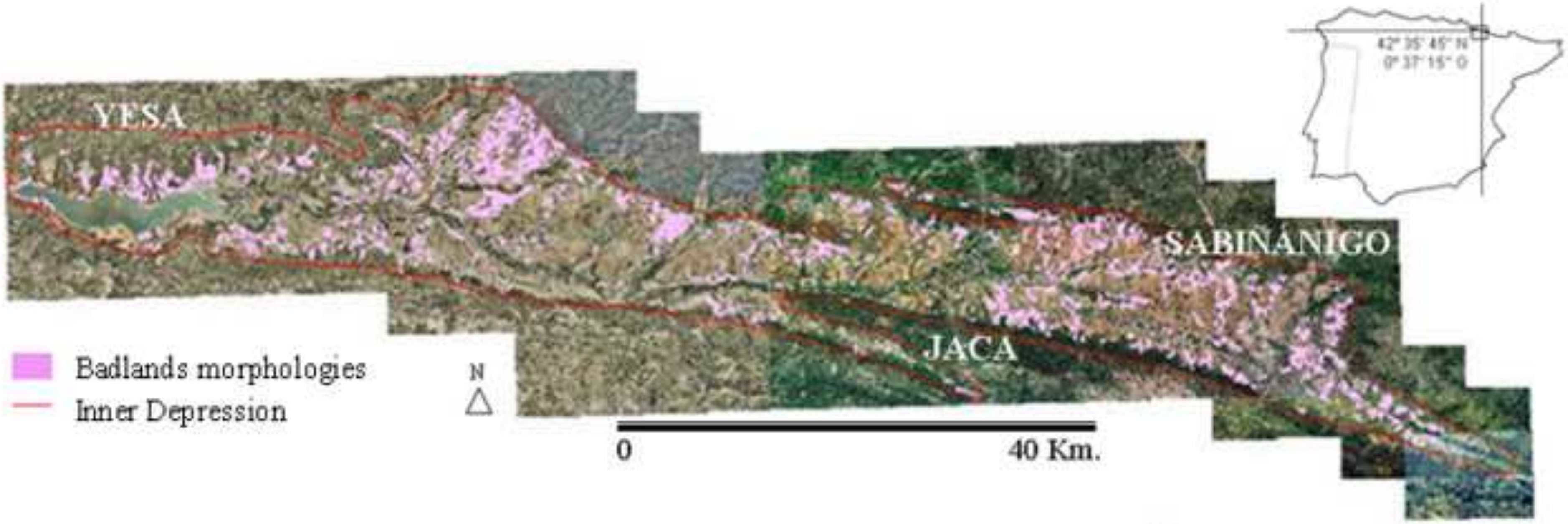
YESA
SABIÑÁNIGO
JACA
Badlands morphologies
Inner Depression
N
0
40 Km.
42° 35' 45" N
0° 37' 15" O

Figure 2

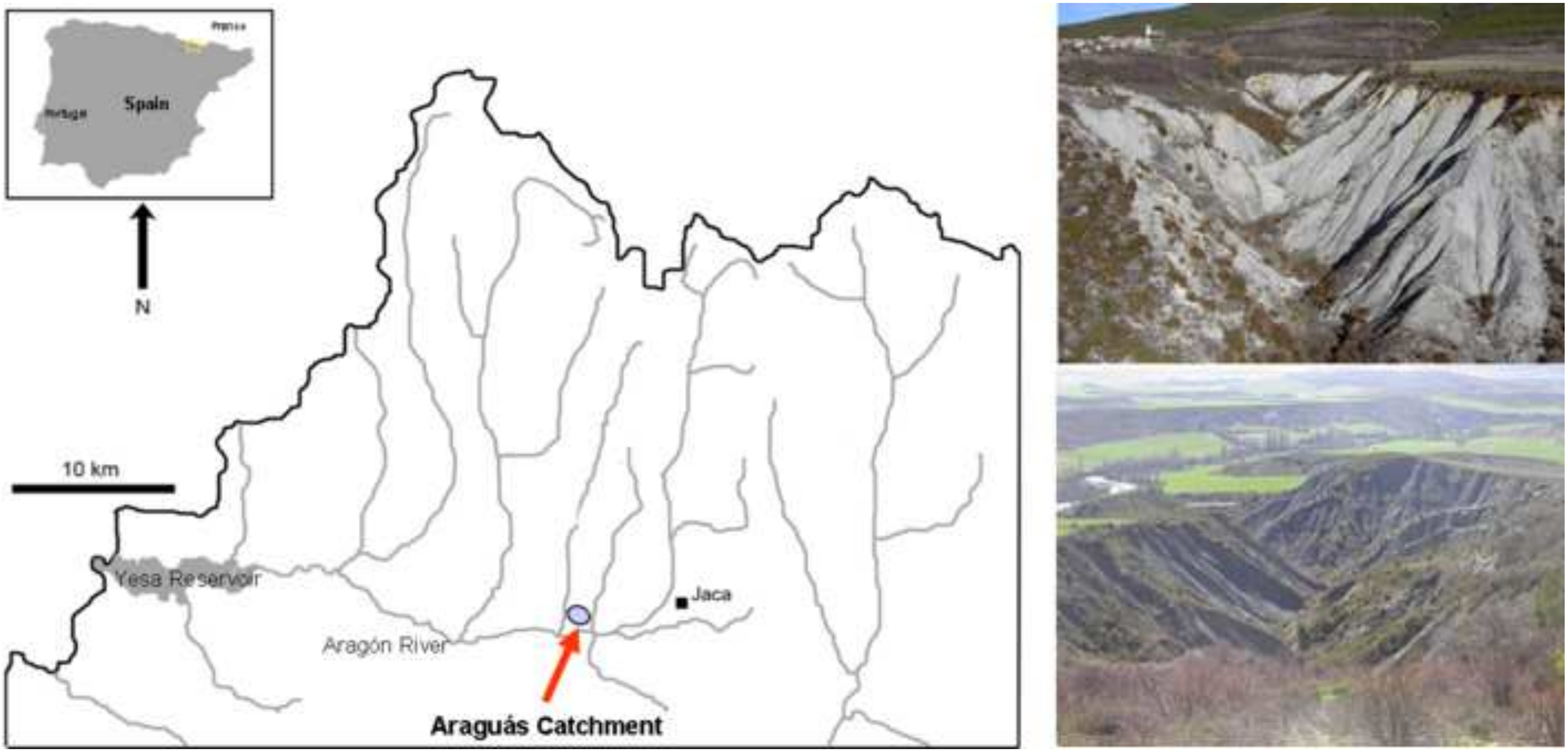
France
Spain
Portugal
N
10 km
Yesa Reservoir
Jaca
Aragón River
Araguás Catchment

Figure 3
Click here to download high resolution image

Figure 4

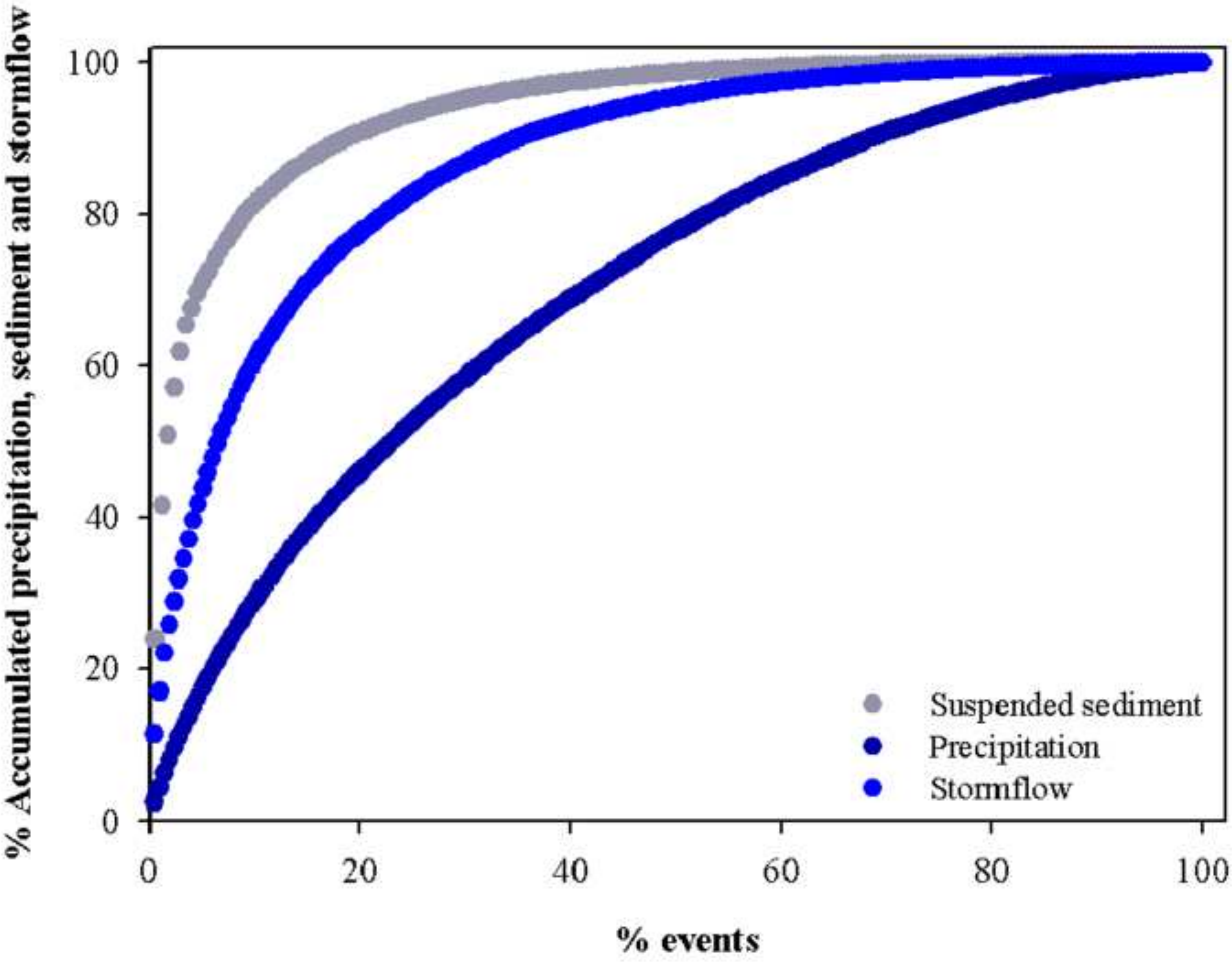
% Accumulated precipitation, sediment and stormflow
100
80
60
40
20
0
0
20
40
60
80
100
% events
Suspended sediment
Precipitation
Stormflow

Figure 5

Click here to download high resolution image

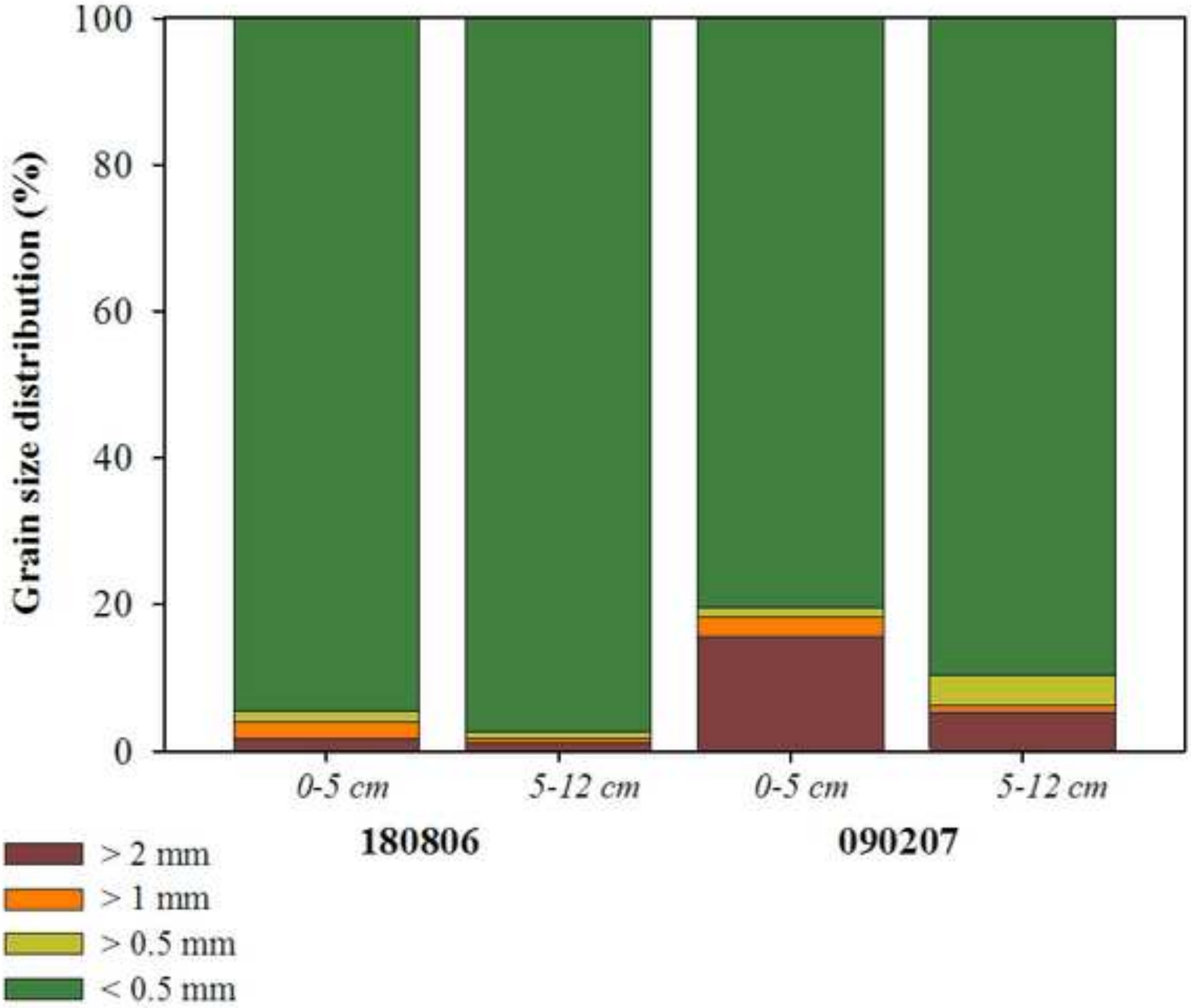

Figure 6

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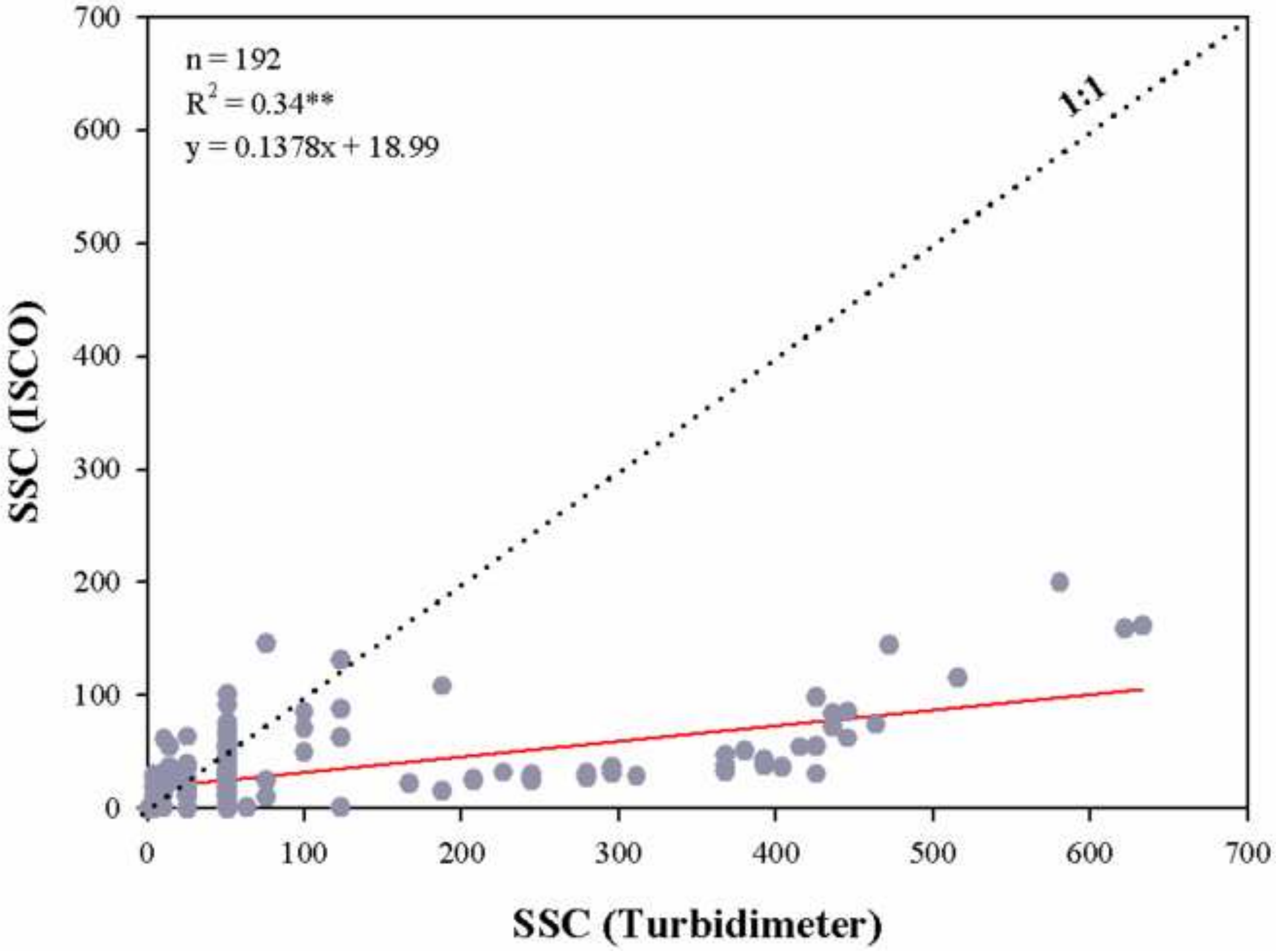


Figure 7

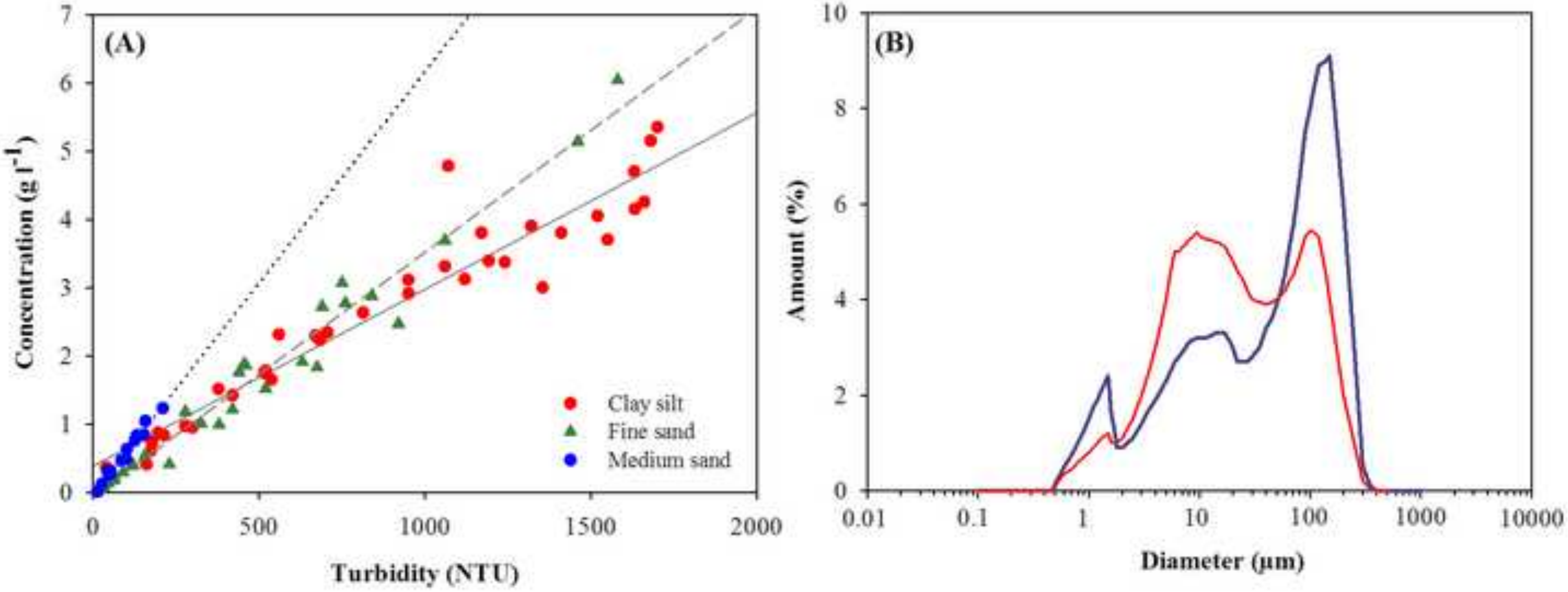
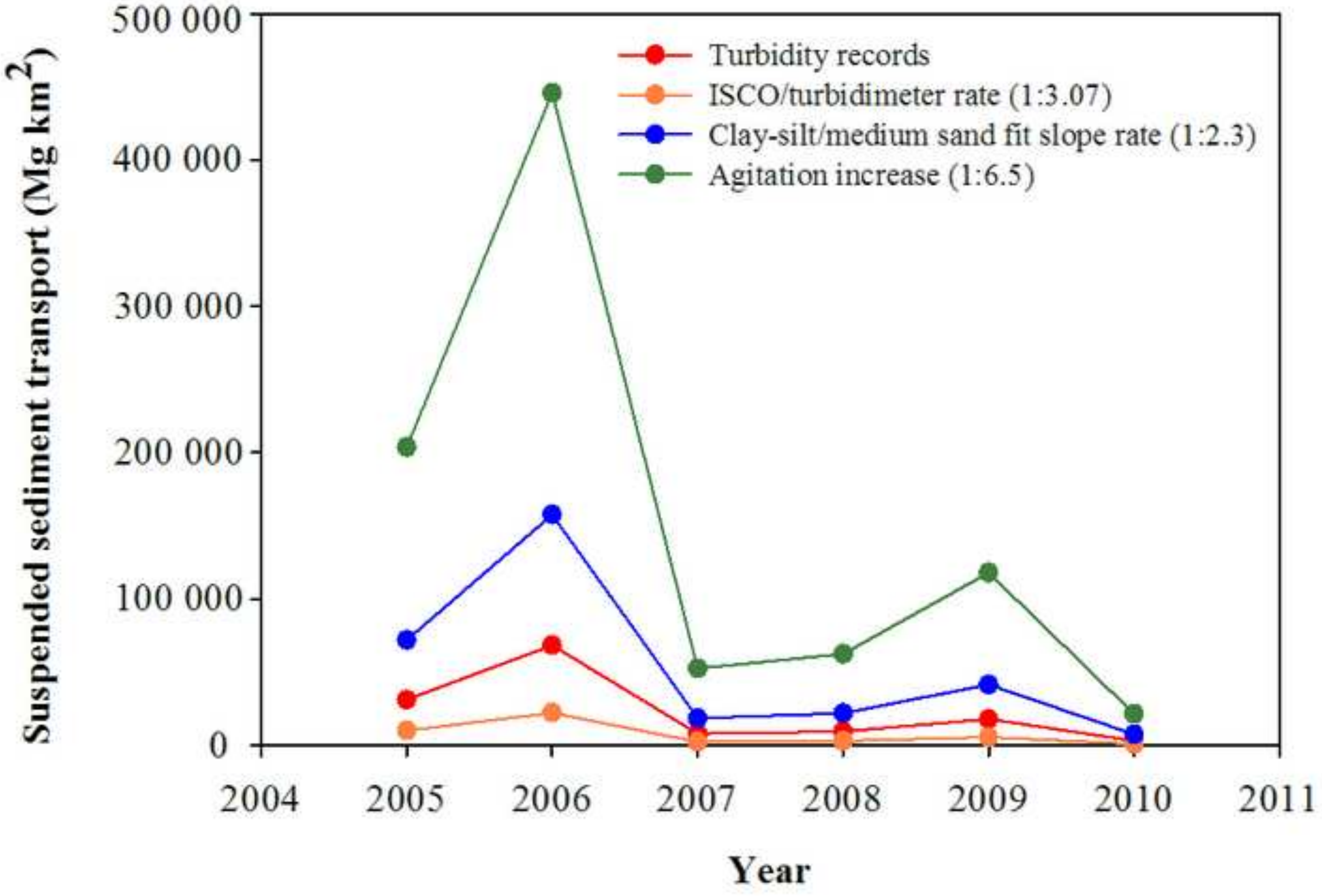

(A)
Concentration (g l^{-1})
0
1
2
3
4
5
6
7
Turbidity (NTU)
0
500
1000
1500
2000
● Clay silt
▲ Fine sand
● Medium sand
(B)
Amount (%)
0
2
4
6
8
10
Diameter (µm)
0.01
0.1
1
10
100
1000
10000

Figure 8


Suspended sediment transport (Mg km^2)
500 000
400 000
300 000
200 000
100 000
0
2004
2005
2006
2007
2008
2009
2010
2011
Year
Turbidity records
ISCO/turbidimeter rate (1:3.07)
Clay-silt/medium sand fit slope rate (1:2.3)
Agitation increase (1:6.5)