HYDROLOGICAL PROCESSES
Hydrol. Process. **28**, 8–15 (2014)
Published online 5 October 2012 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/hyp.9522

Suspended sediment causes annual acute fish mortality in the Pilcomayo River (Bolivia)

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Abstract:

Fish mortality in the middle reaches of the Pilcomayo River (Bolivia), locally called 'borrachera', can be observed almost every year at the onset of the rainy season. In order to study the potential causes of the 'borrachera', suspended sediment (SS) and selected water quality parameters have been monitored from mid-September until mid-December 2010. Gill samples were taken and analysed, before and during the 'borrachera' event on December 7th 2010. Data on river discharge were obtained from a database.
During the sampling period, the river hydrology changed dramatically. At the day of the 'borrachera', heavy rains in upstream reaches of the river catchment changed the river from a quiet stream into a turbulent river with extremely high concentrations of SS ($> 100\,g\,l^{-1}$). This may be caused by the inundation of the entire riverbed, which causes easily erodible material, left on the riverbanks at the end of the former rainy season, to be transported by the river during the first peak discharges.
As concentrations of heavy metals in filtered water samples did not show higher values during the 'borrachera', it is concluded that the 'borrachera' is unlikely to be caused by heavy metal toxicity. Results showed a strong association between the SS concentration and the 'borrachera'. Gills of fish collected during the 'borrachera' were clogged with sediment to such an extent that oxygen uptake became virtually impossible. High SS concentrations are therefore considered to be the cause of this typical fish mortality phenomenon. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS borrachera; fish mortality; suspended sediment; Pilcomayo River; Bolivia

Received 21 May 2012; Accepted 15 August 2012

INTRODUCTION

Excessive sediment loads act as an ecosystem stressor in rivers. Concentration, duration of exposure, composition and particle size of sediment loads in rivers have a strong impact on the biota present. Therefore sediment regimes of rivers should be managed to prevent excessive sediment pressures on the aquatic habitats and their species (Berry *et al*., 2003; Collins *et al*., 2011). Fish communities must be adapted to the local sediment regime. Enhancement of suspended sediment (SS) loads due to upstream erosion can be a naturally occurring phenomenon due to climate but can also be caused by human impact such as expansion of agricultural land, intensification of farming practises and deforestation (Collins *et al*., 2011; Kemp *et al*., 2011). However, in particular, enhanced fine sediment loads are known to have indirect and direct negative impacts on freshwater fish with varying survival response across different species (Kemp *et al*., 2011 and literature therein). Fine SS can for example cause clogging of fish gills or bring contaminants in the water (Collins *et al*., 2011), which can lead to fish kills (Bruton, 1985; Ryan, 1991; Buermann *et al*., 1997; Lake and Hinch, 1999). In the Olifants River (South Africa), for example, fish mortalities were associated with a drastic increase in SS concentrations, from $25\,g\,l^{-1}$ to more than $70\,g\,l^{-1}$, caused by the construction of a reservoir (Buermann *et al*., 1995, 1997).

A type of sudden and massive fish mortality of unknown cause, locally known as the 'borrachera', is a phenomenon in the Pilcomayo River (Bolivia). This phenomenon occurs in the middle reaches of the Pilcomayo River (Gran Chaco) and can be observed almost every year at the onset of the rainy season. The Spanish word 'borrachera' literally

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means drunkenness and is derived from the typical behaviour of the fish during this phenomenon. Throughout, a 'borrachera' fish show uncoordinated swimming and come to the water surface gasping for air. After a while, they remain floating, dead or unconscious, at the water surface. A typical event does not last longer than half a day, after which some surviving fish may fully recover.

Usually, the 'borrachera' takes place during a period in which the water level of the river is rising rapidly. The local human population anticipates this event: from the moment the water level of the Pilcomayo River starts to rise, people gather along the river banks to wait for a possible 'borrachera', which means an easy catch. Although in some years, a 'borrachera' is lacking, in most years, one or occasionally two events occur. There is a lot of speculation about the actual causes, as until now, scientific studies on this phenomenon have been lacking.

As the 'borrachera' typically takes place at the onset of the rainy season, causes related to water current velocity, sediment transport or water chemistry might be involved (Smolders *et al*., 2004). Temporary high metal discharges from upstream mining activities, for instance, can be lethal (Garcia-Guinea and Huascar, 1997; Hudson-Edwards *et al*., 2001).

A high concentration of (fine grained) SS may also play an important role. SS concentrations measured in the Pilcomayo River vary enormously, i.e. from less than $0.05\,g\,l^{-1}$ during the dry season to up to $60\,g\,l^{-1}$ during the rainy season (Smolders *et al*., 2002, 2003). These high concentrations in the Pilcomayo River are mainly caused by natural erosion of the Andean mountain region (Iriondo, 1993; Smolders *et al*., 2002; Stassen *et al*., 2010). Previous monitoring programs did not measure SS concentrations in the Pilcomayo River on a daily base, which means that day-to-day variations did not become apparent. Such variations, however, could be important for the occurrence of a possible 'borrachera' phenomenon, since it takes place during less than a day.

The main aim of this research was to reveal a possible relationship between the 'borrachera' in the Pilcomayo River and short-term changes in concentrations of SS and water quality. In order to answer this question, we formulated the following specific research questions.

1) Does a relationship exist between river discharge, SS concentrations and the occurrence of the 'borrachera'?
2) Is clogging of fish gills with sediment during a 'borrachera' a cause of the observed acute fish mortality?
3) Are increased dissolved metal concentrations a possible cause of the 'borrachera'?

MATERIALS AND METHODS

Study area

The Pilcomayo River in Bolivia is one of the few hardly regulated and therefore nearly natural river systems of South America. Previous research in the Pilcomayo River has focussed mainly on metal contamination (Smolders *et al*., 2003), water chemistry (Smolders *et al*., 2004) and fish population dynamics (Bayley, 1973; Payne and Harvey, 1989; Mochek and Pavlov, 1998; Smolders *et al*., 2002; Dzerzhinskii, 2004; Stassen *et al*., 2010). The river is populated by various potamodromous fish species, which are an important human food source and therefore of great economic value for the region. Especially, the Sábalo *Prochilodus lineatus* (Valenciennes, 1837) is of major importance for commercial fishing (Smolders *et al*., 2002; Stassen *et al*., 2010). Sábalo catches appear to depend strongly on river discharge, which is significantly influenced by the ENSO-phenomenon (Smolders *et al*., 2000, 2002; Stassen *et al*., 2010).

The catchment of the Pilcomayo River (Figure 1) has a size of approximately $272\,000\,km^2$ and is located in the central part of the South American continent (Figure 1).

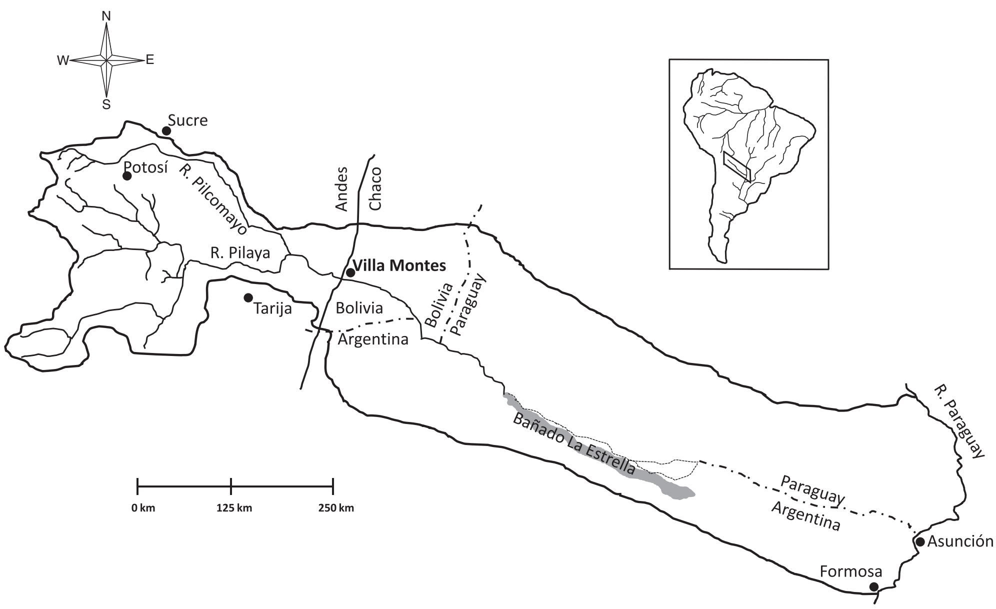

Figure 1. Map of the Pilcomayo catchment. Sample location Villa Montes in bold

It includes a variety of environments among which mountains, semiarid plains and wetlands (Stassen *et al.*, 2010). The origin of the river is located between the high Andean peaks (Cordillera Oriental) in Bolivia at an altitude of 5000 m above sea level.

The upper 500 km of the river is located in the mountainous region of the erosion sensitive Bolivian Andes, with a mean slope of 10 ‰ (Smolders *et al.*, 2002). Near the town of Villa Montes, the river reaches the semiarid Chaco plains at an altitude of 400 m above sea level, where it continues its course for about 1000 km. Entering the Chaco plain, the river changes from a mountainous river with rapids and narrow canyons, into a breached river system, and ultimately into a lowland river system with a mean slope of 0.2 ‰ (Smolders *et al.*, 2002). The lower reaches of the river form a megafan system, where the river disappears into a huge marsh area at the border region between Paraguay and Argentina (Bañado La Estrella, Figure 1). This marshland area is located in an alluvial fan system which is formed by the river by deposition of vast amounts of sediment (Iriondo, 1993). This deposition has interrupted the direct confluence with the Paraguay river and the river has retreated itself as a consequence (Figure 1; Iriondo, 1993; Smolders *et al.*, 2002).

Field work

From mid-September 2010 until mid-December 2010, samples of water and SS were collected in the Pilcomayo River, near the town of Villa Montes in Bolivia (Figure 1). These samples were taken approximately on a daily basis. Furthermore, the river was checked daily for the presence of dead fish, and local fishermen were instructed to alert the research team in case of any observed fish mortality. Discharge data of the Pilcomayo River at Villa Montes were obtained from the 'Comisión Trinacional para el desarrollo de la Cuenca del Rio Pilcomayo' (Internet reference 1).

During sampling water temperature, water current velocity and pH were measured directly in the field. Water temperature and pH were measured with a Schott, Handylab pH11. Water samples were filtered in the field by means of Rhizon soil water samplers (Eijkelkamp Agrisearch, The Netherlands). Filtered water samples were acidified directly with concentrated nitric acid (1 ml per 100 ml water) in order to maintain metals in solution. Samples were stored in pre-washed polyethylene containers at $-20\,^{\circ}C$ until analysis.

Depending on the SS concentration of the river water, 1–50 l of water was collected in pre-washed containers. SS samples were always collected at the same location in the river and were taken at a water depth of approximately 0.6 m below water surface. After the SS had settled, the water layer was removed carefully. Subsequently, the sediment was dried (48 h, at 70 °C), weighed and stored in pre-washed polyethylene containers.

Fish samples were collected in September 2010, well before the onset of the rainy season (reference samples) and during the 'borrachera'. For the reference situation, ten fish of *P. lineatus*, Bagre *Pimelodus* sp. and Boga *Leporinus* sp. were obtained from local fisherman. During the 'borrachera', ten specimens of *P. lineatus* and four specimens of *Leporinus* sp. were collected from dead fish, floating in the water. No specimens of dead or unconscious *Pimelodus* sp. were found during the 'borrachera'. The fish collected during the 'borrachera' were probably dead for at least several hours. Fish weight, total length and sex were recorded. The gills were rinsed thoroughly with distilled water. The gill runoff, containing sediment accumulated on the gills, was dried in an oven (48 h, at 70 °C), and stored in pre-washed polyethylene containers until analysis.

Analysis

The grain size distribution of SS and sediment collected from the gills was assessed with a laser diffraction technique (Malvern Particle Sizer type 3600 Ec) at the Centre of Estuarine and Marine Ecology in Yerseke (The Netherlands).

Water samples were analysed for Sodium on an inductively coupled plasma emission spectrophotometer (ICP-AES, IRIS Intrepid II, Thermo Electron Corporation, Franklin, MA). Metals and metalloids of water samples, were analysed using inductively coupled plasma mass spectrometry (ICP-MS, X series-Thermo Fisher Scientific). Blanks and reference samples were run as quality controls.

RESULTS

Occurrence of 'borrachera'

A 'borrachera' was observed on the 7th of December 2010. Fish lay dead or unconscious on the riverbanks or floated on the water surface (Figure 2). The observed dead specimens included *P. lineatus*, *Leporinus* sp. and Surubi *Pseudoplatystoma coruscans* (Spix & Agassiz, 1829). Remarkably, no dead *Pimelodus* sp. were observed, although species of this genus are known to be abundant in the river in this period of the year.

Figure 2. Dead fish observed on the river banks during the 'borrachera' in the Pilcomayo River near Villa Montes

River discharge and SS

During the sampling period which coincided with the transition from the dry season to the rainy season, discharge values ranged between $30\,m^3\,s^{-1}$ and $200\,m^3\,s^{-1}$; later in the rainy season (in February), discharge even increased to more than $2000\,m^3\,s^{-1}$ (Figure 3). During the day of the 'borrachera', river discharge reached a peak value of $167\,m^3\,s^{-1}$ (Figure 3).

The transitional phase in between the dry season and the rainy season is typically characterized by a dramatic change of the rivers hydrology. SS concentration varied enormously during the period of sampling (Figure 3). Initially SS concentrations were low ($<0.1\,g\,l^{-1}$) with river discharges between 20 and $40\,m^3\,s^{-1}$. In between mid-September and mid-October, it rained several times in the region of Villa Montes. This, however, seemed to have little effect on the river discharge and SS concentration near Villa Montes. The river's first serious increase in discharge and SS concentration took place in the second half of October. Rain events in the upstream Andean part of the river resulted in a small increase of the river discharge ($55\,m^3\,s^{-1}$) and a relatively strong increase of the SS concentration to almost $35\,g\,l^{-1}$ on the 22nd of October. The river water was very muddy and contained organic debris such as wood. In Villa Montes, people gathered along the river during this day to look for signs of a possible 'borrachera', which, however, did not occur. Next, during the entire month of November, river discharge and SS concentrations remained low, corresponding to values measured earlier in September (Figure 3).

On the 7th of December, river discharge suddenly increased from $38\,m^3\,s^{-1}$ (measured on the 6th of December) to $167\,m^3\,s^{-1}$. This increased discharge coincided with the 'borrachera' (Figure 3, arrow). During this 'borrachera', the SS concentration increased from $3.7\,g\,l^{-1}$ on the 6th of December 2010 to a peak value of $104\,g\,l^{-1}$ on the 7th of December 2010. During the following days, SS concentrations dropped again to levels below $20\,g\,l^{-1}$. During the days following the 'borrachera', river discharge decreased to values comparable to the period before the 'borrachera' ($30\,m^3\,s^{-1}$). At the end of December, the river discharge started to increase again, to levels characteristic for the rainy season, with values which were consistently higher than $100\,m^3\,s^{-1}$, and with peak values of approximately $2000\,m^3\,s^{-1}$ in February and March (Figure 3, inset).

Fraction size distribution of SS

The particle size distribution of SS as well as the concentration of SS fluctuate significantly in the Pilcomayo River (Figure 4). The major part of SS (60–100%) consists of very fine particles (silt fraction). From mid-September until mid-October, the fraction with a particle size >63 μm was relatively high (20–40%) compared to the rest of the monitoring period (<10%). From September 24th, the SS concentration and the fraction of SS <63 μm increased for several days, without a change of river discharge. Since mid-October, the fraction with a particle size >63 μm remained low and only occasionally increased to contribute 10% or more (Figure 4), usually without a corresponding change of river discharge. In general, the fraction >63 μm was higher when SS concentrations were below $0.1\,g\,l^{-1}$.

On the 7th of December, during the 'borrachera', discharge and water current velocity increased, and the SS size distribution shifted with a relatively higher contribution of the fractions >63 μm, although the SS size distribution remained dominated by fractions <63 μm (Figure 4).

Fraction size distribution of sediment on the gills

Observations on fish focussed on three species, viz. *Pimelodus* sp., *P. lineatus* and *Leporinus* sp. *Pimelodus* sp. live near the sediment surface, while *P. lineatus* and *Leporinus* sp. mainly occupy the middle and upper parts of the water column. During the reference situation in September, the gills of none of the examined fish did

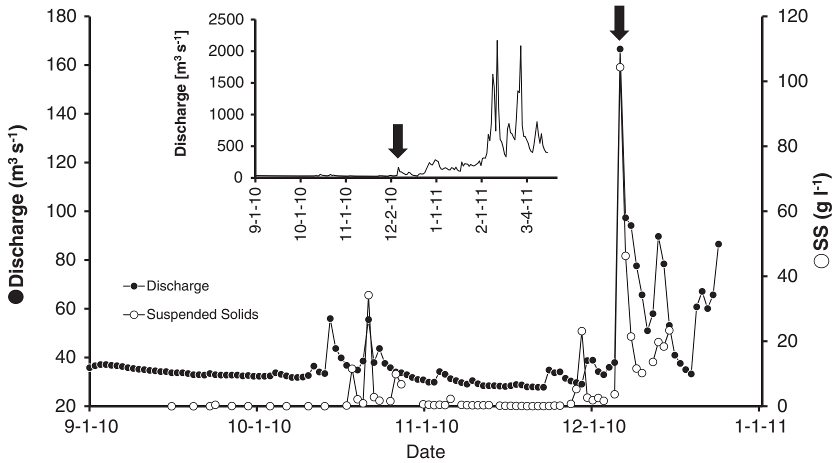

Figure 3. Discharge (left hand y-axis) and suspended sediment concentrations (SS, right hand y-axis) of the Pilcomayo River near Villa Montes between September 2010 and January 2011. A black arrow highlights the 'borrachera'. The inset shows the discharge of the Pilcomayo River between September 2010 and March 2011 (note the different scale of the y-axis)

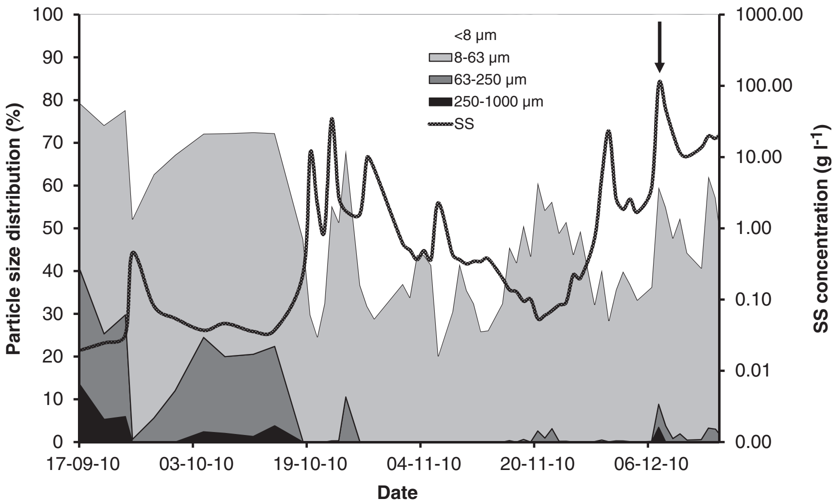

Figure 4. Relative fraction size distribution (left hand y-axis) and suspended sediment concentrations (SS, right hand y-axis) of the Pilcomayo River near Villa Montes between September 2010 and January 2011. The black arrow highlights the 'borrachera'

contain any sediment. Gills collected from fish that died during the 'borrachera', however, were completely clogged with sediment (Figure 5) due to the high SS concentration of the river.

The particle size distribution of the accumulated sediment in the different gills sampled during the 'borrachera' showed – in spite of high variation – a general pattern (Figure 6). Bars have been sorted on fish size and species, from the smallest at the left to the biggest at the right. The bar on the far right side is the corresponding fraction size distribution of SS in the river on the day of the 'borrachera'. The fraction of particles >63 µm was higher on the gills compared to the SS in the river (right bar). The quantities of accumulated sediment on the gills varied between 0.59 and 2.27 g g^{-1} dw (Figure 6).

Water quality

During the sampling period, water temperature varied between 25 °C and 30 °C. The Pilcomayo is an alkaline river with pH values between 7.8 and 8.6 in the dry season. During the onset of the rainy season, peak events caused a temporal drop in pH. During the 'borrachera' on the 7th of December, a pH value of 7.1 was measured, and on the 22th of October, a pH value of 7.3 was measured.

Figure 5. Gills of *Prochilodus lineatus* collected during the 'borrachera' in the Pilcomayo River clogged with sediment

After such events, pH values restored rapidly to levels between 7.8 and 8.6.

Sodium and some potentially toxic metals in filtered water samples from the Pilcomayo River showed strong fluctuations (Figure 7). Sodium concentration showed a decrease since the second half of November. During the 'borrachera', dissolved metal concentrations showed relatively high values (Figure 7). However, earlier in the season, higher metal concentrations have been measured, without causing fish mortality. The heavy metal concentrations have been compared with monitoring results of 1997 and 2006 (Stassen and Van de Ven, 2007; unpublished data), both monitoring programs showing more or less similar values for dissolved metal concentrations.

DISCUSSION

Within the monitoring period, dead fish were only observed during the 'borrachera'. Fine sediment in suspension can directly damage gills as a result of erosion of the mucus coating, abrasion of tissue and interrupted gaseous exchange as fine particles bind directly to the gill epithelium and clog rakers and filaments (Kemp *et al*., 2011). Gill samples showed that high concentrations of SS during the 'borrachera' coincided with an extreme clogging of the gills with sediment, which very probably caused serious respiratory problems (Cordone and Kelley, 1961; Bruton, 1985; Ryan, 1991; Kemp *et al*., 2011), resulting in the observed acute mass fish mortality.

High concentrations of fine SS in rivers are well known to affect fish (Buermann *et al*., 1997; Lake and Hinch, 1999; Crowe and Hay, 2004). For Redbreast tilapia *Tilapia rendalli* (Boulenger 1897), LC50 values for SS concentration ranged between 21–24 g l^{-1} (juveniles) and 42–48 g l^{-1} (adults) (Buermann *et al*., 1997). In a laboratory study with Coho salmon *Oncorhynchus kisutch* (Walbaum, 1792), mortality was not observed until SS concentration reached values of about 100 g l^{-1} (Lake and Hinch, 1999). Although these lethal

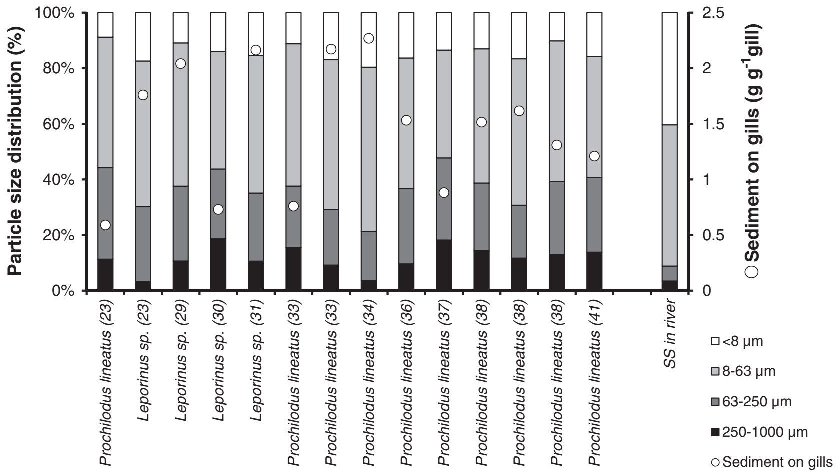

Figure 6. Relative fraction size distribution (left hand y-axis) and quantities of accumulated sediment on the gills of fish (right hand y-axis) collected during the 'borrachera' event in the Pilcomayo River. Fish size (TL) is given in centimetres between brackets behind the fish species name

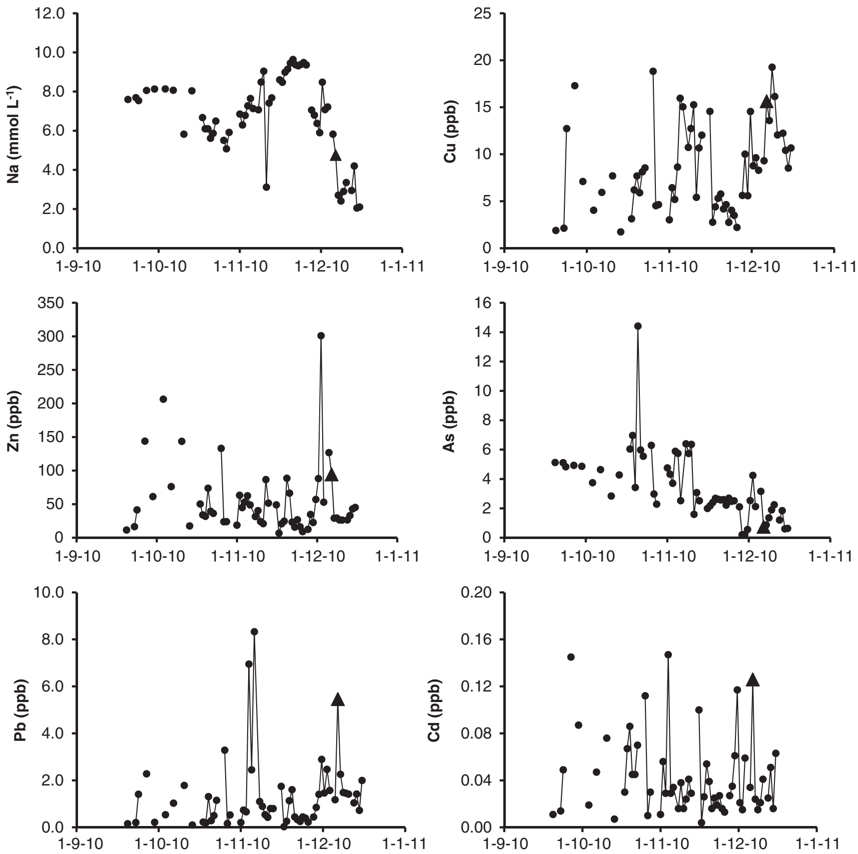

Figure 7. Variation of sodium and some potentially toxic metals in filtered water samples from the Pilcomayo River. Samples taken during the 'borrachera' event are indicated with a triangle

SS concentrations correspond to other fish species, it can be concluded that SS concentrations of more than $100\,g\,l^{-1}$ measured during the 'borrachera' might very well be the cause of the observed fish mortality in the Pilcomayo River, irrespective of possible other causes which may have contributed to the mortality.

Remarkably, no dead *Pimelodus* sp. were observed, although they are known to be abundant in the river in this time of year. However, *Pimelodus* sp. might resist higher SS concentrations because of their benthic way of life, while *P. lineatus* and *Leporinus* sp. mainly occupy the middle and upper parts of the water column. The absence of dead *Pimelodus* sp., however, could also be explained by the low buoyancy of *Pimelodus* sp. The swim bladder of *Pimelodus* sp. is adjusted to stay at or near the water bottom (Alexander, 2009) and dead *Pimelodus* sp. may therefore remain below the water surface.

Sodium concentrations showed a decrease in time due to dilution, which is caused by the increase of rainfall over time (Smolders *et al.*, 2004). Concentrations of heavy metals in filtered water samples did not show higher values during the 'borrachera' than on other sampling dates. The occasionally higher concentrations of heavy metals might be caused by mining activities in the upstream part of the catchment (Hudson-Edwards *et al.*, 2001; Smolders *et al.*, 2003). Because of the pH of approximately 7.8 to 8.6, heavy metals are bound to SS and are hardly bio-available for fish (Chen *et al.*, 1997). It is thus concluded that the 'borrachera' is unlikely to be caused by heavy metal toxicity.

Local rainfall near Villa Montes does not have a significant effect on the river's discharge. However, heavy rains in the upstream Andean part of the catchment can change the river from a quiet stream in the centre of the riverbed into a turbulent river which occupies the entire riverbed from one day to another (Smolders *et al.*, 2002, 2004). The SS concentration on the 7th of December (104 g l^{-1}) was the highest value measured during the monitoring period. Relative to the discharge, SS concentration during the 'borrachera' was much higher compared to values obtained for the rainy season from previous monitoring programmes (Figure 8) (Smolders *et al.*, 2002). In general, SS concentrations tend to be higher between September and January, which can be explained by the phenomenon that during the first half of the rainy season the most erosion sensitive soils are flushed into the river (Wood and Armitage, 1997; Smolders *et al.*, 2002) (Figure 8).

The extremely high SS concentration during the 'borrachera' may be caused by the inundation of the entire riverbed, which causes easily erodible material, left on the riverbanks at the end of the former rainy season, to be transported by the river during the first peak discharges (Wood and Armitage, 1997). The observed clockwise hysteresis loop indicates a decrease of sediment availability during the flood period (Williams, 1989; Lefrançois *et al.*, 2007). This may explain why the 'borrachera' usually takes place only once a year and at the onset of the rainy season. Although SS concentrations are typically very high during the entire rainy season (10–50 g l^{-1})

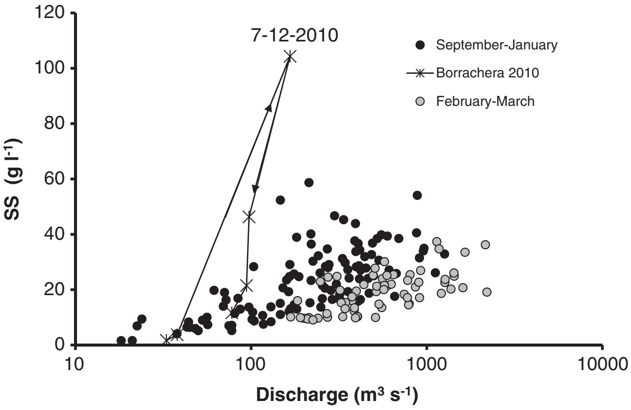

Figure 8. Suspended sediment (SS) concentration *versus* discharge during the 'borrachera' compared with data available from previous monitoring programs (Smolders *et al.*, 2002)

(Figure 8), values as high as during the 'borrachera' are never reached (Smolders *et al.*, 2002).

SS size distribution can be affected by rain events in upstream areas with erosion prone soils (Martin and Meybeck, 1979). During the entire monitoring period, fraction size distribution of SS was dominated by fractions <63 µm. In the dry season, solute transport is limited (Figure 3) (Smolders *et al.*, 2002) and largely consists of stream bed material which has a larger proportion of relatively coarser material. In the first month of the monitoring period, the SS content therefore contains a larger fraction of particles >63 µm. The upstream parts of the catchment are dominated by small sized easily erodible material (Iriondo, 1993). Rainfall in these areas in the rainy season therefore results in a relative increase of small-sized particles (<63 µm) in the river. At the day of the 'borrachera', an increase of the fraction >63 µm indicates that also coarser material was transported. The sudden increase of the discharge leads to the inundation of the complete river bed, and the water current apparently becomes sufficiently strong to transport the river bed material. During the 'borrachera', the high sediment load probably consisted of river bed material diluted by fine (<63 µm) eroded material from the river catchment.

The fraction >63 µm is higher for sediment collected from the gills, compared to the SS of the river during the 'borrachera'. A possible explanation for this is that initially the larger sized particles become trapped more easily in between the gill filaments in comparison to smaller sized particles. The smaller fractions can then settle down when the spaces between the gill filaments become smaller, due to the settling of bigger sized particles. In this way, the presence of a coarser fraction of SS in the river's water during the 'borrachera' may enhance clogging of fish gills.

CONCLUSION

The 'borrachera' on the 7th of December 2010 clearly coincided with a very high SS concentration which was well within the range known to be potentially lethal for (other) fish species and also provoked a serious clogging of the gills. Therefore, it is concluded that the high SS concentrations caused the observed mortality on the 7th of December 2010.

Experiments in tanks in which different fish species are exposed to different SS concentrations, and different particle size distributions could give more insight in the susceptibility of the different species from the Pilcomayo River.

ACKNOWLEDGEMENTS

The authors wish to thank Mr. T. van der Steeg, R.C. Salazar Armella, F. Rojas, E. Alpiri Ayala and J. Rohof for assistance in the field. P. van der Ven, J. Eygensteyn, P. Klaren and E. Pierson are acknowledged for assistance during laboratory analysis and W. Suykerbuyk and T. Bouma for grain size distribution analyses. D. Hering is acknowledged for his valuable comments on an earlier version of the article.

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