Fine Sediment Input and Benthic Fauna Interactions at the Confluence of Two Large Rivers

Blettler, M.C.M.[1]*, Amsler, M.L.[1], Ezcurra De Drago, I.[1], Drago, E.[1], Paira, A.[1], Espinola, L.A.[1], Eberle, E.[1] and Szupiany, R.[2]

[1]Instituto Nacional de Limnología (INALI-CONICET-UNL), Ciudad Universitaria (3000), Santa Fe,

Argentina

[2]Universidad Nacional del Litoral (UNL), Facultad Ingeniería y Ciencias Hídricas, FICH. Ciudad

Universitaria (3000), Santa Fe, Argentina

ABSTRACT: Several studies suggest that invertebrate abundance and richness are disrupted and reset at confluences. Thus, junctions contribute disproportionately to the overall aquatic biodiversity of the river. In general terms, authors have reported high abundance and diversity due to the major physical heterogeneity at junctions. However, data are still scarce and uncertainties are plentiful. The impact of a great input of fine sediments on the distribution patterns of benthic invertebrates at a river confluence was quantitatively analyzed herein. The junction of the subtropical Bermejo River (high suspended sediment load) with the large Paraguay River is the selected study area to achieve this aim. While diversity increased slightly downstream the junction (from 0.21 to 0.36), density and richness of the macroinvertebrate assemblage significantly diminished downstream the confluence (from 29050 to 410 ind/m^2; p< 0.05) due to the input of fine sediment from the Bermejo River (mean fine sediment increased downstream from 6.3 to 10.2 mg/L), causing a negatively impact on invertebrate assemblage. This study highlights the ecological importance of the sediment input effects on benthic invertebrates, a topic still poorly explored in river ecology. It is speculated that the spatial extent of the impact would be dependent upon the hydrological and sedimentological context, highly unequal between both rivers. New hypotheses should be tested through new studies considering different hydrological stages.

Key words: benthic invertebrate, fine sediment load, channel confluence, large river, sedimentology

INTRODUCTION

River channel confluences are critical sites of hydraulic, morphological and ecological change in large rivers, and form nodes connecting sub-basins that may have very different geological and hydroclimatic features (Best *et al.* 2011). Although riverine ecologists recognize the importance of tributary confluences, the ecological role of junctions as sources of physical heterogeneity is not well understood, however this is now changing (Rice *et al.*, 2006). The morphology (channel slope, width and depth, substrate characteristics) and hydraulics of confluences are unusual and may provide unique ecological opportunities for macroinvertebrates (Cianficconi *et al.*, 1991; Rice *et al.*, 2001, 2006; Beckmann *et al.*, 2005; Kiffney *et al.*, 2006). Characteristics at tributary confluences are abrupt changes in water chemistry, organic matter concentration and supplied sediments

(Franks *et al.*, 2002). Field evidence suggests that invertebrate abundance and richness are disrupted and reset at confluences and differences between invertebrate upstream and downstream of confluences are substantially greater than differences between equally spaced sites in the intervening channel links (Rice *et al.*, 2001). Otherwise, elevated physical heterogeneity at confluences could increase biological diversity because of the well-accepted principle that biological diversity tends to increase with habitat variability (MacArthur and MacArthur, 1961). Benda *et al.* (2004) proposed that confluences are biological "hotspots" that contribute disproportionately to the overall aquatic biodiversity of the river (cf. McClain *et al.*, 2003). However, data to evaluate many elements of previous statements are evidently scarce (Rice *et al.*, 2006) and they predominantly come from high latitudes within Europe and North America (Rosales

*Corresponding author E-mail: martinblettler@hotmail.com

et al., 2008).. In addition, little attention has been devoted to the influence of density differences between the confluent flows, which may exist due to dissimilarities in suspended sediment concentrations (Best *et al*. 2011). On the other hand, hydrological dynamic and flooding actually are the driving factors that determine distribution patterns of benthic assemblages in secondary channels of the floodplain system (Thorp *et al*. 2006, Humphries *et al*. 2014). Other authors have linked the presence of streambed patches inhabited by invertebrates with the frequency, intensity and severity of flooding (e.g. Szczerkowska-Majchrzak *et al*. 2010, Rolls *et al*. 2012).

Considering all above argumentation, the impact of a great input of fine sediments on the distribution patterns of the benthic invertebrates in a large subtropical confluence is quantitatively described herein. The junction of the Bermejo River (high suspended sediment load) with the large Paraguay River (basically a clearwater river) is the selected study area to achieve this aim.

This paper is part of a series of large-scale ecological studies completed in the Paraguay and Bermejo Rivers in the frame of the PIP 6209 CONICET project.

MATERIALS & METHODS

The sampling area is localized at the confluence of the Bermejo River with the Paraguay River (northern of Argentina). Four cross-sections were assigned, two of them upstream (cross-sections 1 and 2) and the other ones downstream the junction (cross-sections 3 and 4). Five sampling stations were selected at each cross-section, three of them were located over the sandy mobile bed (termed herein the "central strip") and the other ones at both river banks (left and right; Fig. 1A). All sampling and measurements were performed in

October 2007 at a low and relatively steady water stage of the Paraguay and Bermejo Rivers (Q= 1719 m^3/s and 74 m^3/s, respectively; Fig. 1B). The Fig. 1C shows a great plume of sediments in suspension originated during high water phases (the importance of this phenomenon is explained in the Discussion).

The Lower Paraguay River drains a large alluvial floodplain, with the river being on average 575 m wide and 9 m deep (Drago, 1990), with a mean discharge of 4000 m^3/s (Giacosa *et al*., 2000). On the other hand, the Bermejo River drainage basin covers 133000 km^2 and the channel has a length of 1800 km. Its headwaters are in the Andean Cordillera (Bolivia and northwest Argentina) where the seasonality and intensity of precipitation cause great erosion in the catchment, and thus supply abundant sediment to the river. The suspended sediment concentration of the Bermejo River is up to 40 g/L during high water phases, showing an annual average of 6.5 g/L (Amsler and Drago, 2009).

The importance of the Bermejo River extends far beyond its catchment, as most of the suspended sediment of the large Middle Paraná River comes from the Bermejo, after being supplied by the Paraguay River, reaching the Atlantic Ocean 1630 km downstream of the confluence. The Bermejo River also contributes to the lower section of Paraguay and Paraná rivers. It was estimated an average rate of 91 million tons of fine sediment (silt and clay) per year transported by the Bermejo at the junction (Amsler, 2006). On the contrary, the Paraguay River transports a small amount of fine sediment (around 3% of the Bermejo average) upstream the confluence (Amsler, 2006).

The peak discharges and sediment yields from the Bermejo River normally occur between January and March. The Fig. 2 shows the monthly water stages recorded in the Paraguay and Bermejo Rivers (at Pilcomayo and Colorado ports, respectively) from 2006

Fig. 1. Plan view of the Bermejo and Paraguay Rivers confluence. A, location of sampling cross-sections and stations (2 to 4 = sampling stations located at the central strip; 1 and 5 = bank stations). B and C, satellite images showing the sediment-laden Bermejo fluid within the less-dense water of the Paraguay River during low water stage (October 2007) and flooding, respectively. Note the increased plume of sediments in C.
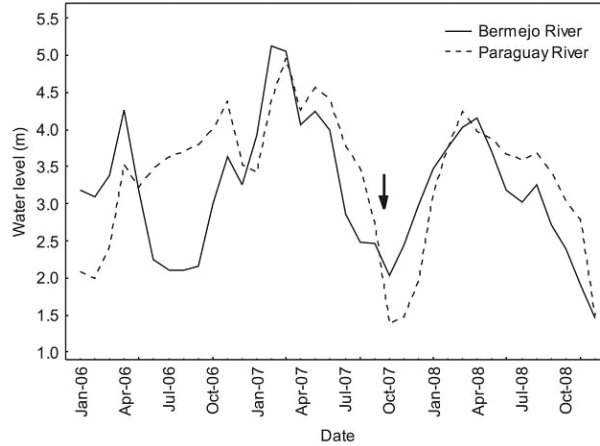
Fig. 2. Monthly water stages from January 2006 to November 2008 at Colorado (Bermejo River) and Pilcomayo (Paraguay River) monitoring stations. Black arrow shows the sampling date.

Table 1. Hydraulic variables measured and computed in the study (α= regression slope coefficient of the relationship current velocity *vs.* depth; p= water density; γ_s = specific weight of sediment; γ_w = specific weight of water; s = γ_s / γ_w ; g = gravity acceleration; d_{50}= median of the bed sediment size distribution).

Name	Symbol	Units	Equation	Description
Current velocity	u	m/s	Direct measurement	Point velocity at each vertical profile
Depth	h	m	Direct measurement	Local depth
Shear velocity	U_*	m/s	$U_* = a / 5.75$	Velocity gradient close to the bed.
Shear stress	τ_0	Kg/m^2	$\tau_0 = U_*^2 \rho$	Bed shear stress derived from shear velocity.
Mobility number	τ_*	none	$\tau_* = \dfrac{\tau_0}{(\gamma_s - \gamma_w)d_{50}}$	Dimensionless relationship between active forces acting on the bed and particle weight.
Mobility-velocity number	τ_{*U}	none	$\tau_* = \dfrac{\overline{U}^2}{g(s-1)d_{50}}$	Version of τ_* using $\overline{U}$ instead of τ_0
Manning's roughness coefficient	n	m$^{1/3}$/s		An estimate of flow resistance in the Manning's formula

to 2008. In order to have a better understanding of the hydrological situation, the water levels are shown more than one year before and after the sampling campaign. This campaign was performed during a regular period of low water stage for both rivers.

The bed morphology of the Bermejo-Paraguay confluence is dominated by a tributary mouth bar that extends from the Bermejo River into the confluence, reflecting the dominance of the Bermejo River sediment load at this site during high water phases. It is noticeable that a central confluence scour, often characteristic of channel junctions with such planform configurations, is absent at this area (Best *et al.*, 2007). Measurements of flow within the confluence show that the Bermejo River forms a density underflow when it

meets the Paraguay River, and generates a flow that moves underneath that of the clearer mainstream water (Best *et al.*, 2007).

The vessel position and river bed topography at the selected at-a-point sampling locations was attained using a Furuno™ GP-1650WF echo sounder coupled to a GPS. The current velocity profiles were obtained using an Ott™ electric propeller current meter, operated simultaneously with the collection of benthic samples. A total of 10-14 point velocities (depending on the local depth) were recorded in the water column at each vertical, with measurements more closely-spaced in the first meter above the bed. Each point velocity was the average value over a 100s measuring period.

Three benthic sample replicates were taken at each sampling station using a Tamura™ clamshell bucket (319 cm^2). Samples were fixed in 5% formaldehyde in the field and filtered with a 200 µm sieve. The invertebrates were hand-picked in the laboratory under a 10x stereoscopic microscope and stored in a 70% ethanol solution. All benthic organisms were counted and identified at species (when possible) and generous level following specific taxonomic keys (see Blettler *et al.* 2012a).

Additional sediment samples for granulometric analysis (by dry sieving) and organic matter estimation (by ignition and subsequent ash-free dry matter weight; g C%), were taken at the same stations. Instantaneous suspended-sediment samples were taken using a horizontal Van Dorn sampler.

The following variables were also recorded in order to characterize the water quality: transparency (Secchi disk; m), water temperature (°C), electric conductivity (µS/cm), pH, bed and surface dissolved oxygen (mg/L), total dissolved solids (ppm), total alkalinity (mg/L CaCO$_3$), bicarbonate (CaCO$_3$ mg/L), Carbonate (CaCO$_3$ mg/L), Chloride (mg/L), total hardness (mg/L CaCO$_3$), Calcium (mg/L), Magnesium (mg/L), Potassium (mg/L), Silicon (mg/L) and Sodium (mg/L).

The characterization of the river hydraulics near the bed at each sampling station was attained by direct measurements of the local velocity profiles, flow depth (h), mean bed sediment particle size (d_{50}) and distribution, and an estimation of the bedform height at a given point. These parameters are the necessary inputs to compute hydraulic variables (see definitions in Table 1) such as the bed shear stress (τ_0), or its equivalent the bed shear velocity (U_*), the sediment mobility number (τ_*) and the "mobility-velocity number" (τ_{*U}). τ_* is a widely-used dimensionless variable in river science and involves the relationship between the tractive forces trying to move the bed particles, as given by τ_0, and the particle weight per unit area (as given by the submerged density of sediment in water ($\gamma_s - \gamma_w$) and mean grain size (d_{50}; passive force) that resist that movement. Moreover, τ_{*U} is a modification suggested by Yalin (1977) of the conceptually similar mobility number, but with the practical advantage that its calculation is simpler since it is based on the local mean velocity ($\overline{U}$), instead of τ_0 for the estimation of τ_*. In addition, the Manning's roughness coefficient was also estimated.

The methodological details concerning to the estimation of these variables in a large river are given in Amsler *et al.* (2009), and specifically for the Paraguay River in Blettler *et al.* (2012a). The values of τ_0 were computed based on the *a* slopes of the velocity/depth

fitted curves (Kostaschuk *et al.*, 2004) and then fitted, in turn, to a logarithmic distribution considering the virtual origin following the *ad hoc* procedure (Perry and Joubert, 1963). All values of r^2 ranged between 0.81-0.98, denoting a reliable setting for computations.

As normality of macroinvertebrate data was verified after log transformation, an ANOVA one-way test was conducted to determine differences between total benthic and *Narapa bonettoi* densities (the key species of the system; see below) at each cross-section. The post-hoc Fisher test was applied in all cases to identify the significant differences between the ANOVA results.

In order to test spatial differences in benthic assemblage patterns, multivariate analyses were used. The canonical analysis of principal coordinates (CAP; Anderson and Willis, 2003) is a constrained ordination procedure which was conducted herein to identify differences in density together with richness species between each cross-section (upstream and downstream the junction) as well as between sampling stations located in the central strip and channel banks. CAP analysis was conducted using the software CAP (Anderson, 2004). The PERMANOVA analysis was then used to identify the significant differences between the CAP results (MULTIV computer program, version 2.4.2; Pillar, 2006). In addition, the Principal Components Analysis (PCA) was applied to identify major environmental gradients in relation with sampling stations location. Finally, biodiversity (Shannon index), species evenness and species richness were also estimated.

RESULTS & DISCUSSION

A total of 46 species were identified in the studied reach, of a total of 60 samples. Total invertebrate densities, considering all sampling stations (20), ranged from 79376 ind/m^2 (cross-section 1) to 112 ind/m^2 (cross-section 4). The median of the total and *N. bonettoi* densities at each cross-section are shown on Fig. 3A and B, respectively. *N. bonettoi* is the key species of the active bed assemblage (Blettler *et al.* 2012a, b) and clearly the most abundant species recorded in this study.

The typical assemblage of invertebrates adapted to the sand bed channels of the Paraná-Paraguay hydrosystem, termed the "active bed assemblage" (Blettler *et al.*, 2012a) was recorded at each cross-section. This is a very sensitive assemblage which only inhabits running waters with clean sandy bed and low organic matter contents along nearly 3500 km in the Paraguay-Paraná river hydrosystem (Takeda *et al.*, 2001; Marchese *et al.*, 2005; Ezcurra de Drago *et*
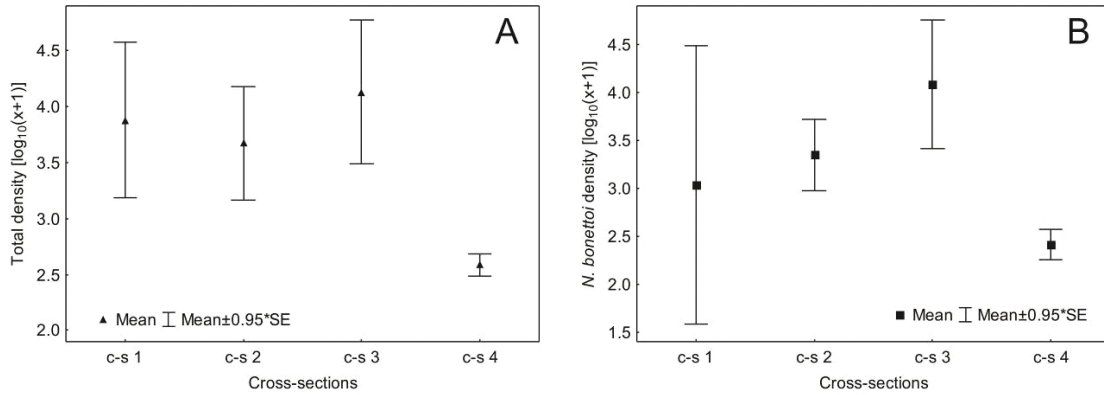
Fig. 3. Whisker plot showing the logarithmic values of total densities (A) and *N. bonettoi* densities [log₁₀ (x+1)] (B) at each selected cross-sections. Note the strong depletion of the invertebrate density in the cross-section 4 (c-s 4). (*): Paraguay River, downstream the junction (c-s 3). Where (a), (b) and (c)= cross-sections located in the Paraguay River at 18km, 15km and 13km upstream the Bermejo confluence (respectively); (f), (g) and (h)= cross-sections located in the Bermejo River at 2.3km, 1.5km and 1km upstream the junction; (k), (l) and (m)= cross-sections located in the Paraguay River at 13km, 15km and 18km downstream the Bermejo confluence (respectively). Additional data taken from Blettler *et al*. (2014).
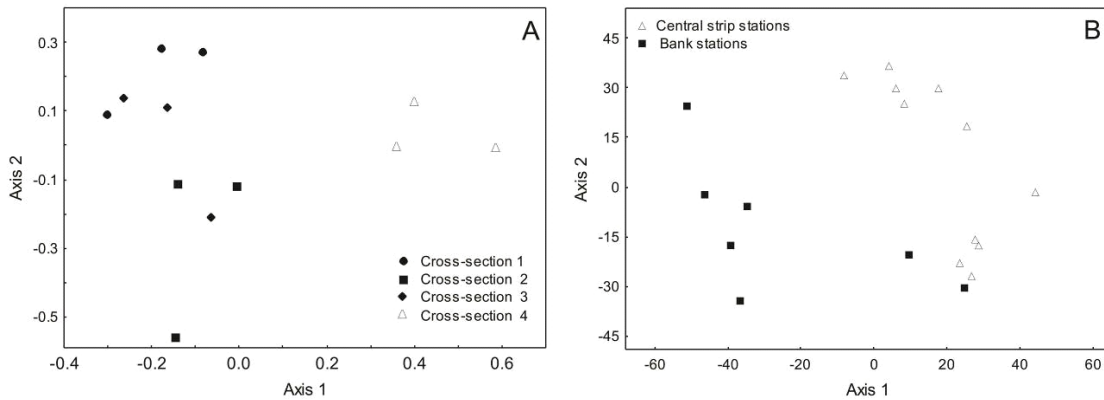
Fig. 4. Ordination plot of the Canonical Analysis of Principal Coordinates showing significant differences in the composition and relative abundance of benthic invertebrates between cross-sections (A) and location in the channel (B; generated with the first two principal coordinate axes from the computed results).

al., 2007; Blettler *et al*. 2008, 2012a, b). Similarly as recorded by those authors, in this study the Oligochaete *N. bonettoi* was the dominant taxa of this assemblage and the key species of the system, followed in density by *Myoretronectes paranaensis* (Turbellaria), *Haplotaxis aedeochaeta* (Oligochaeta), *Tobrilus* sp. (Nematoda), *Potamocaris* sp. (Copepoda) and *Corynoneura* sp. (Chironomidae). In all cases, changes in density of *N. bonettoi* were closely linked with those in total density, increasing and decreasing proportionally (Fig. 3A and B). The result of ANOVA test shows a significant difference in densities (total as well as *N. bonettoi* densities) between cross-sections 1-2-3 and cross-section 4 ($F_{(3, 6)} = 7.8$, p= 0.01; $F_{(3, 6)} = 13.8$, p = 0.004, respectively), as shown in Fig. 3.

The analyses of fauna density/richness using CAP show that the samples could be classified into two

benthic groups according to each studied cross-section (T= 1.94, p= 0.02; 999 random permutations; Fig. 4A). The PERMANOVA result confirms that the invertebrate assemblage from cross-sections 1-2-3 are statistically different regarding to the cross-section 4. The CAP analysis was also used to test differences in density and richness between samples taken at banks and central strip of the channel (Fig. 4B). The result shows clearly two differentiable invertebrate assemblages for each riverine habitats (T= 2.57, p= 0.02; 999 random permutations). Otherwise, no significant differences were recorded between sampling stations located at left and right banks (T= 0.9, p= 0.06, 999 random permutations; plot not shown herein).

On the other hand, another benthic assemblage, called "bank assemblage" (Blettler *et al*., 2012a), was found at both banks of the channel (Fig. 4B; with few

Table 2. Values of physical variables (measured and calculated). *bOM*: percentage of organic matter in the bed sediment; *n*: Manning's roughness coefficient; *SS fine*: concentration of suspended fine sediments; *% sand*: percentage of sand in the bed sediment; *% clay*: percentage of clay in the bed sediment; d_{50}: median of bed sediment distribution; *SS sand*: concentration of suspended sand.

Sampling Cross-sections	$\bar{u}$ (m/s)	τ_0 (Kg/m²)	d_{50} (mm)	τ_*	τ_{*U}	bOM (gC%)	n	SS fine (mg/L)	SS sand (mg/L)	% sand	% clay	Secchi (cm)
1.2	0.60	0.133	0.55	0.147	40.21	0.116	0.027	3.87	40.13	98.75	0.56	51
1.3	0.39	0.786	0.75	0.635	12.80	0.154	0.107	3.87	40.13	99.51	0.28	51
1.4	0.40	0.048	0.23	0.126	42.44	0.656	0.024	3.87	40.13	97.68	1.26	51
2.2	0.62	0.123	0.73	0.102	32.97	0.137	0.023	8.23	46.17	96.97	1.88	52
2.3	0.62	0.054	1.65	0.020	14.30	0.286	0.017	8.23	46.17	98.11	0.3	50
2.4	0.34	0.081	0.2	0.245	35.32	0.276	0.036	8.23	46.17	97.73	1.35	48
3.2	0.58	0.062	0.7	0.054	30.13	0.095	0.018	6.97	43	99.01	0.64	49
3.3	0.55	0.147	0.65	0.137	29.02	0.094	0.028	6.97	43	99.32	0.33	43
3.4	0.48	0.122	0.24	0.308	59.61	0.254	0.032	6.97	43	98.98	0.6	41
4.2	0.53	0.119	0.5	0.144	35.15	0.169	0.028	10.2	55.6	96.78	1.46	49
4.3	0.51	0.213	0.24	0.538	66.61	0.788	0.040	10.2	55.6	46.61	6.3	43
4.4	0.43	0.275	0.35	0.476	33.27	0.084	0.053	10.2	55.6	99.44	0.21	25
Left bank	0.23	-	-	-	-	1	-	55.3	7.1	57.4	11.6	48
Right bank	0.26	-	-	-	-	1.3	-	73.8	14.4	63	13.7	30

exceptions as this Fig. shows). This assemblage was mainly composed by *Limnoperna fortunei* (Bivalvia), *Cordylophora caspia* (Hydrozoa), P*aranadrilus descolei, Brinkhurstia americanus, Aulodrilus pigueti, Pristina americana* (Oligochaeta) and *Aelosoma* sp. (Polychaeta). This assemblage is well adapted to the typical hydraulic and bed sediment conditions at banks, i.e. slower flowing water which encourages the deposition of the finest particles, and higher bed organic matter concentration (Table 2). This table shows that slightly higher τ_{*U} values as well as a fining of the sand size fraction were found in the cross-section 4, together with a remarkable increased concentration of fine and coarse sediment in suspension. A decreasing transparency occurs on this cross-section which is more evident in the c-s4.4 sampling station (close to the right bank). Note that it was not possible to estimate bed hydraulic variables at the bank stations (left and right), since the velocity profiles did not follow a logarithmic distribution. The physical variables significantly correlated with the total invertebrate density were d_{50} (p= 0.01; r²= 0.43), τ_{*U} (p= 0.01; r²= 0.44), fine sediment in suspension (p= 0.02; r²= 0.43) and sand sediment in suspension (p= 0.05; r²= 0.31).

Otherwise, the first axis of the Principal Component Analysis (PCA) explained 74.4% of the physical variations while the second one explained 15%, and both axes together explained 89.4%. The cross-section 4 remained separated from the others, ratifying that the higher values of fine and coarse sediment in suspension, τ_{*U} as well as clay concentrations characterized this sampling section (Fig. 5).

According with these results, the Bermejo River represents an abrupt increase in the supply of water and suspended sediments downstream the confluence (see Table 2, Fig. 5 and its inset). Invertebrates belonging to the active bed assemblage shown a dramatically impoverished density and richness downstream the Bermejo River junction (Table 4; Fig. 3A, B and 5A) with increasing quantity of sand and fine sediment in suspension, in spite of the appropriate percentage of bed sand sediment and bed hydraulic stresses found there (Table 2; for a detailed characterization of optimal ranges of physical condition enabling this assemblage settlement confers Blettler *et al.*, 2008, 2012a). Those results are in agreement with the findings of Blettler *et al.* (2014) in the same river but considering a significantly larger spatial scale, around 15 km upstream and downstream the Bermejo River junction. According to the CAP results (Fig. 4A) there are clearly two different benthic groups in the active bed, one of them upstream the Bermejo junction (cross-sections 1-2, but surprisingly also including cross-section 3) and the other one downstream the confluence (cross-section 4 only). This fact is explained by the effect of sediment
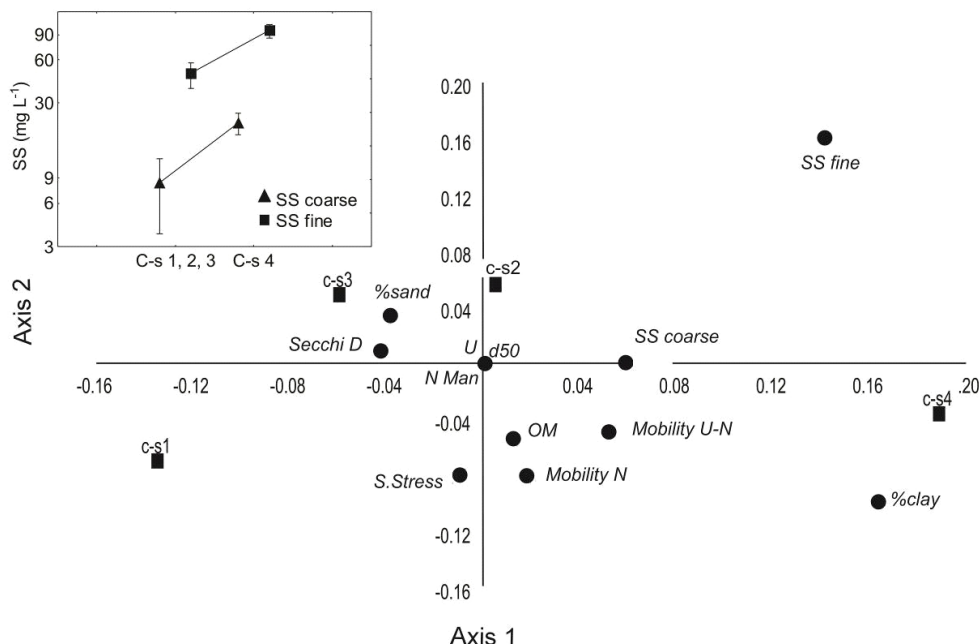
Fig. 5. Plot of scores distribution along principal component analysis (PCA) axe according to physical variables and invertebrate densities recorded in the central strip.

U= water velocity, *%sand*= percentage of bottom sand, *%clay*= percentage of bottom clay, *S.Stress*= shear stress, *N Man*= Manning´s roughness coefficient, *Mobility U-N*= Mobility-velocity number, *Mobility N*= Mobility number, *SScoarse*= coarse suspended sediments, *SSfine*= fine suspended sediment, *OM*= bed organic matter, *Secchi D*= water transparency. The inset highlights the increasing fine/coarse sediment in suspension at each cross-section.

loading on invertebrate assemblage and also suggests that this effect does not occur immediately after the junction but a few kilometers downstream. Thus, in spite of the high sediment input from the Bermejo River, the invertebrates inhabiting the cross-section 3 (500 m downstream the confluence) are practically unaffected by this supply. Since both rivers maintain remarkable differences in discharge and water density, when the Bermejo attains the Paraguay its flow is keeping on the right bank under the influence of the Paraguay flow, remaining most sediment on this bank without apparent ecological consequences. However, at least 5 km downstream (cross-section 4) the suspended sediments are mixed by the Paraguay flow, expanding entirely over the channel with a negative impact on invertebrate settlement (dramatic richness and density reduction). Closely connected with this, it should be remarked that the unusual sedimentological characteristics of the Bermejo maintain a very poor and limited benthic assemblage inhabiting this river (Ezcurra de Drago *et al*., 2004; Blettler *et al*., 2014).

It has been well documented that sediment inputs, from different origins, modify the assemblage structure and density of benthic communities (Bond and Downes, 2003; Death *et al*., 2003; Harrison *et al*., 2007; among others). As individuals succumb to the direct

negative impacts of increased sediment loads, changes occur in the abundance of individual species, which in turn change the assemblage composition (Fossati *et al*., 2001; Ehrhart *et al*., 2002; Freeman and Schorr, 2004; among others). However, in the present study the effect of sediment delivery from the Bermejo River is not necessarily a direct consequence of the sedimentation phenomenon itself. According to Best *et al*. (2011), the bed morphology of the Paraguay River at the Bermejo confluence is dominated by an accumulation of sediment that originates from the Río Bermejo during a the water phase. However, in this study that accumulation of sediment was not clearly detected at the cross-section 4 (5 km downstream), where the invertebrate depletion was evident. This fact could be explained for an expansion/contraction dynamic of the sediment accumulation given by the hydrological fluctuation.

Since the present sampling campaign was performed during a low water stage, it is expected a reduction of the accumulation area. The stability of this area may be dictated largely by a density underflow which moves across channel underneath the fluid of the Paraguay River (Best *et al*. 2011). Therefore, considering the clear increase of suspended sediment delivered by this river during flooding stages,

Table 3. Water quality variables measured upstream and downstream the junction. Note the similar values recorded at both reaches.

Water quality variables	Units	Upstream junction	Downstream junction
Total alkalinity	mg/L $CaCO_3$	33	32
Bicarbonate	mg/L $CaCO_3$	33	32
Carbonate	mg/L $CaCO_3$	No detected	No detected
Chloride	mg/L	17	18
Total hardness	mg/L $CaCO_3$	33	33
Calcium	mg/L	4.9	5.2
Magnesium	mg/L	3.6	3.8
Potassium	mg/L	2.3	2.4
Silicon	mg/L	No detected	No detected
Sodium	mg/L	14	17
Electrical water conductivity	µS/cm	145	149
Dissolved O_2 (near surface)	mg/L	8.3	7.7
Dissolved O_2 (near bottom)	mg/L	7.2	6.5
pH	none	7.3	7.2
Total dissolved solids	ppm	70	74
Water temperature	°C	24.1	23.7

it is probably that at least four factors may contribute to explain the effects of suspended fine sediment input on the benthic invertebrates (see Blettler *et al*., 2014). First, the sedimentary dynamics at Bermejo-Paraguay junction likely present a large physical barrier (1-2 km approximately) which does not developed immediately after the confluence. This blockage is formed by the significant input of sediment by the Bermejo River, increasing and decreasing in size during high and low water stages, respectively. Thus, the bed under this fine sediment plume would not be viable to be colonized itself or being difficult during high water level stage to be crossed by invertebrates. Second, in the case of any invertebrates that break through this physical barrier, the normal colonization of the reach after the junction would be very hard because of the changes in size of the bed sand. According to Kaufmann *et al*. (2009) when the input of fine sediment from the Bermejo to the Paraguay River increases (particularly during flooding events), the average size of bed particles becomes smaller and the interstices between the larger particles become filled with finer sediment. Actually, in this study was recorded a significant increase of fine sand and very fine sand percentages downstream the junction (30 and 20%, respectively). Without interstitial pore spaces free of fine sediments, the active bed assemblage of invertebrates cannot live (Takeda *et al*., 2001; Blettler *et al*., 2008). On the contrary, during low water periods they become coarser with more free interstitial spaces. The effect of this fining and coarsening sequence of grain size on organisms (during low and high water stages, respectively) involves a considerable delay given by a certain time of colonization required by organisms after substrata modification. Therefore, the persistent fining and

coarsening of the grain size, due to the temporal changes in grain size delivered during the Bermejo River hydrograph, would cause an extremely dynamic situation on the river bed, preventing regular colonization by invertebrates. The Fig. 1C shows the extreme sediment load during a high hydrological stage. Third, declines in phytoplankton quality can occur because of the effect of turbidity on algal growth (Parkhill and Gulliver, 2002), whereby suspended sediment reduces light penetration, resulting in a decreasing algal growth and therefore food availability for invertebrates (Quinn *et al*., 1997). Downstream of the Bermejo River confluence, the phytoplankton community on the Paraguay is severely reduced (Zalocar de Domitrovic, 2007) due to the huge sediment input and consequent reduction in light penetration with the obvious impact to invertebrates. Fourth, the suspended fine sediment is in continuous movement and contact with the top layers of bed sand, constantly being deposited and suspended by the flow. This would likely cause the penetration of fine sediments into the interstitial spaces of the sand, leading its clogging (Packman *et al*. 2000). In addition, the fine sediment particles may act as an abrasive if moving at high velocity. Unprotected fleshy body parts are particularly prone to this type of damage, with obvious consequences for the individuals affected (Newcombe and MacDonald, 1991). However, these four hypotheses should be tested through new studies considering different hydrological stages.

On the other hand, the direct association of taxa distribution with bed hydraulic characteristics has been shown in several researches around the world (e.g. Statzner *et al*., 1988; Fuller and Rand, 1990; Holomuzki and Messier, 1993; Quinn and Hickey, 1994; Hart *et al*.,

Table 4. Shannon´s diversity index, evenness and species richness at each selected cross-section (c-s 1, 2, 3 and 4).
Note that it was also included information from cross-sections located in the Paraguay River at 18km, 15km and 13km upstream and downstream the Bermejo River confluence as well as from the Bermejo River itself (2.3km, 1.5km and 1km upstream the junction). Additional data were taken from Blettler *et al.* (2014).

Sampling sections	Shannon's Index	Evenness	Richness
Paraguay R. Upstream (c-s 1)	0.13	0.11	16
Paraguay R. Upstream (c-s 2)	0.41	0.3	24
Paraguay R. Upstream (c-s 3)	0.09	0.07	17
Paraguay R. Downstream (c-s 4)	0.36	0.6	4

1996; Rempel *et al.*, 2000). This close association has been also recorded in the Paraguay and Paraná Rivers to $\bar{u}$, τ_0, τ_* and τ_{*U} (Blettler *et al.*, 2008, 2012a, b; Amsler *et al.*, 2009; summarized by Wantzen *et al.*, 2014). However, in the present study these hydraulic variables had a scarce significance (excepting the τ_{*U}). This is a very important fact, which is explained as follow. Sedimentological variables like fine and coarse sediment in suspension as well as d_{50} have shown a significant association with spatial distribution of benthic invertebrates (Table 2, see *p* values of the correlation above). In this study these variables were the best explanatory for benthic spatial distribution. While the sediment size distribution (d_{50}) is slightly lower and the τ_{*U} is a little higher in the cross-section 4, the sedimentological variables shown the largest values with regard to the other cross-sections (Table 2, Fig. 5). Therefore, those small differences in hydraulic values would not be the main reason to explain the strong modifications to the benthic assemblage downstream of the Bermejo River junction. Conversely, the massive increase of fine and coarse sediment in suspension downstream the confluence is thus interpreted as the main reason for the fauna depletion.

As it is evident in Table 3, the chemical water quality upstream and downstream the Bermejo River junction remains unchanged.

The junctions of tributary rivers are usually associated with profound changes in the chemical water (Pretty *et al.*, 2006), supplemental nutrients, organic and inorganic pollution (Kiffney *et al.*, 2006), etc. However, in the present study the values of chemical variables are clearly similar upstream and downstream reaches as Table 3 shows. An optimal water quality (upstream as well as downstream) was registered during the sampling campaign, i.e. chemical variables are in the natural values expected in this fluvial system (Depetris and Pasquini, 2007). In addition, all chemical variables are within the appropriate range of chemical water quality to the invertebrate assemblage development (Blettler *et al.*, 2008). In this sense, chemical characteristics cannot explain by themselves

the ecological pattern of the species distribution and composition recorded herein, reaffirming the previous statement that the massive increase of fine and coarse sediment in suspension is the main reason for the density and richness fauna depletion.

In agreement with studied performed at high latitudes within Europe and North America (Rice *et al.*, 2001), the differences between the invertebrate assemblages upstream and downstream were substantially greater than differences between equally spaced sites in the intervening channel links. Benda *et al.* (2004), based on data from several rivers of Canada, suggested that confluences act as biological "hotspots" that contribute disproportionately to the overall aquatic biodiversity of the river. According to these authors, elevated physical heterogeneity at confluences increases biological diversity. However, Benda *et al.* (2004) recognized that there is limited empirical evidence demonstrating the ecological benefit of morphologically diverse tributary junctions. Although in this study the biological diversity and species evenness slightly increased after Bermejo confluence (see Table 4, cross-section 4), the richness and density dramatically decreased (about 4 and 85 times, respectively). In the light of these results it should be remembered that the Shannon index basically arises from the proportion $pi = ni N-1$, where ni is the number of individuals in species *i* and N is the total number of individuals in the assemblage, thus its ecological interpretation should be made with care. Although the diversity values in this study slightly follow the tendency suggested by Benda *et al.* (2004), both results suggest different ecological sceneries. Herein, the notorious depletion of invertebrate richness and density denote a negative impact of the input of fine sediment coming from the Bermejo River.

CONCLUSIONS

1. While diversity increased slightly downstream the junction (from a mean of 0.21 to 0.36), density and richness of the macroinvertebrate assemblage significantly diminished (from 29050 to 410 ind/m², and from 19 to 4 species; respectively) due to the input of fine sediment from the Bermejo River (from 8.3 to 22

mg/L of coarse suspended sediments, and from 48 to 98 mg/L of fine suspended sediments), causing a negatively impact on invertebrate assemblage.

2. It is speculated that the spatial extent of the impact would be dependent upon the hydrological and sedimentological context, highly unequal between both streams (during the current sampling campaign it was recorded $Q = 1719$ m^3/s to the Paraguay River and 74 m^3/s to the Bermejo River), i.e. relatively high water discharges and low sediment loads in the Paraguay River compared with those in the Bermejo River (48 mg/L and 490 mg/L of fine suspended sediments; respectively). The different combinations of discharges and loads arriving at the junction especially during high stages (do not measured yet) would be crucial to modulate the downstream impact on the benthic fauna.

3. Bed hydraulic variables showed a lower significance than sedimentological variables to explain the invertebrate distribution downstream the junction (see Table 2 and Fig. 5).

4. The "central strip assemblage" is proper for testing the impact of suspended sediment load on invertebrates. In contrast, the "bank assemblage" apparently would not be suitable for this purpose.

5. This study highlights the importance of the sediment input effects on benthic invertebrates, a topic still poorly explored in river ecology. Further developments of this kind of studies considering both, anthropogenic and natural sources of fine sediment inputs, are required to improve river management techniques in large alluvial rivers.

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