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Bedload transport in a river confluence

J.P. Martín-Vide, A. Plana-Casado, A. Sambola, S. Capapé *

Technical University of Catalonia-BarcelonaTech, Barcelona, Catalonia, Spain

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ABSTRACT

The confluence of the regulated Toltén River and its tributary the unregulated Allipén (south of Chile) has proved dynamic in the last decade. Daily bedload measurements with a Helley–Smith sampler, bed surveys, and grain-size distributions of the two rivers are obtained from a field campaign that lasts 3 months in high-flow season. The goals are to quantify total bedload and to understand the balance between tributary and main river and the bedload distribution in space and texture. The bedload transport varies 200-fold, with a maximum of 5000 t/day. The discharge varies five-fold, with a maximum of 900 m^3/s. Two-thirds of the total bedload volume are transported through the deeper area of the cross section and gravel is predominant (64%). Average bedload volumes in the confluence seem unbalanced in favour of the tributary. Main river bedload transport is predominantly at below-capacity conditions, while the tributary bedload transport is at-capacity conditions. This is deemed the main reason of inaccuracy of the bedload predictors. The roles of entrainment into suspension, helical flow, partial transport, and mobile armour are discussed.

1. Introduction

River Toltén originates in the Andes and flows toward the Pacific Ocean through the region of Araucanía in the south of Chile (Fig. 1). A run-of-river hydropower plant is projected for the river, consisting of a low-head cross-river weir equipped with sluice gates and a canal intake in the right bank. The weir location, directly downstream of a confluence, will allow the runoff of the tributary and main river basins to be used (a total drainage area of 5700 km^2). The main river and the tributary are gravel-bed rivers. The planform of the river at the confluence is highly dynamic. These facts raised concerns on whether sand, gravel, or even coarser material transported by both rivers could clog the intake of the future hydropower development and result in costly maintenance needs to keep the intake free of sediment. The high uncertainty associated with sediment transport computations warranted a field campaign during the feasibility phase of the project. The study focused on bedload transport because, essentially, a partial barrier such as a low-head weir would not obstruct the suspended load. The opening of the sluice gates at the future weir would partially purge the coarse material, but dredging would likely be required to deal with the remaining sediment. Detailed knowledge of bedload transport is critical to assess the risk of clogging of the intake and to estimate dredging needs. This paper presents the results of the field campaign conducted in 2013 to quantify the total bedload at the location of the planned facility.

In addition, given that data on bedload transport in river confluences are scarce, the new data and the past and present river morphology at the confluence are analysed in order to obtain a deeper understanding of the system.

Fluvial dynamics at the confluence of two streams have attracted considerable attention in the last three decades. Scale models of braided rivers (Ashmore and Parker, 1983) and laboratory experiments of the junction of rectangular channels (Biron et al., 1996; Qing-Yuan et al., 2009) have resulted in the identification of several hydro- and morphodynamic features such as a shear layer that forms along the junction of the two streams; a separation area, caused by the deflection of the tributary, prone to create a bar; a bed discordance (*i.e.*, the tributary bed elevation is higher than the main river bed elevation) that ends in an avalanche face; and a scour hole that appears downstream of the crossing of the tributary and main river alignments (Fig. 2). Numerical models have been tested in the particular conditions of a river confluence (Lane et al., 2000; Roca et al., 2008). A prevailing objective of research has been to identify the factors that control the depth and location of scour holes. Some of the studied factors are the confluence angle, the discharge ratio (defined as the ratio of the tributary discharge over the main river discharge), and the bed discordance.

Because of the difficulties associated with the extrapolation of laboratory results to real cases, field investigations are becoming an increasingly popular tool in the study of confluences (Parsons et al., 2007). At first, the insight gained through experimentation was used to interpret real case studies for which limited measurements were available (Best, 1987, 1988). Unfortunately, most of the case studies for which extensive field data are available deal with creeks and small rivers (Roy and Bergeron, 1990; Rhoads, 1996; Leclair and Roy, 1997; Rhoads and

* Corresponding author at: Technical University of Catalonia-BarcelonaTech, c/ Jordi Girona 1, D1-204, 08034 Barcelona, Catalonia, Spain.
E-mail address: sergi.capape@upc.edu (S. Capapé).

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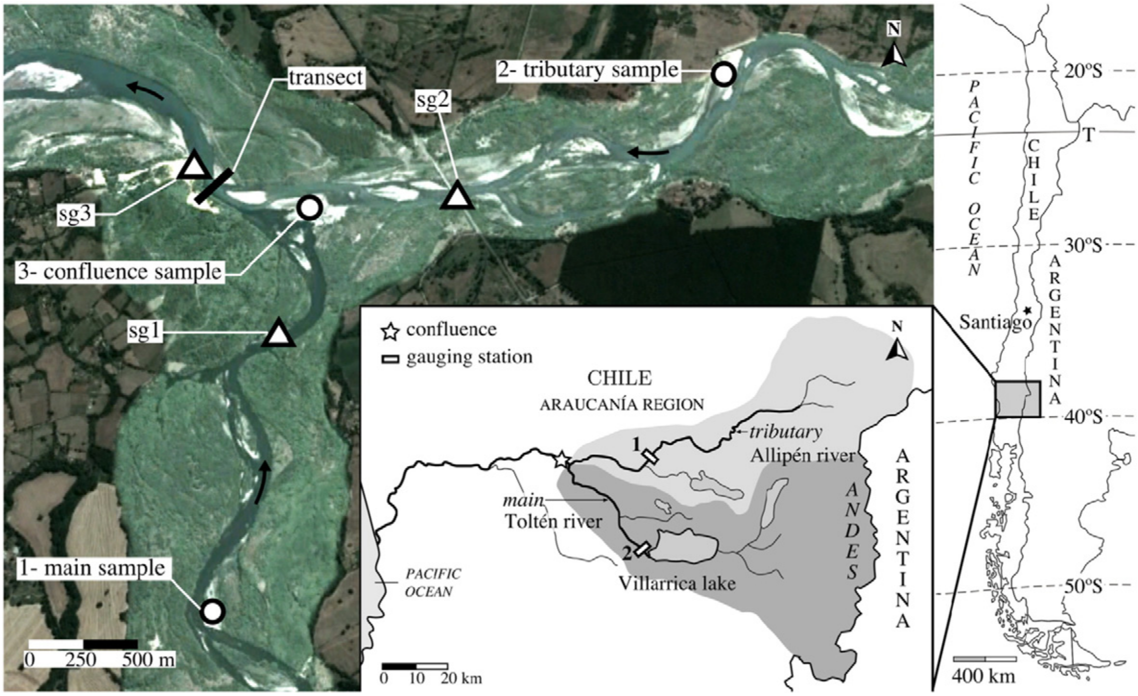

Fig. 1. General view of the study area: the confluence of the Toltén (main river) and the Allipén (tributary), the position of the staff gauges (sg1, sg2, and sg3), and the locations of the collected bed material samples. Staff gauge sg1 was secured to a rock of the left river bank, sg2 to a bridge pillar, and sg3 to the rock outcrop that dominates the plain. The distances between sg2 and sg3 and between sg1 and sg3 are 1425 and 1326 m, respectively, along the river course. Insert: location map with the two subbasins and the Chilean Water Agency gauging stations.

Kenworthy, 1998; Rhoads and Sukhodolov, 2001, 2008; Best and Rhoads, 2008). A noteworthy exception is the Paraná River, a large braided system with multiple confluence–diffluence units (Parsons et al., 2007, 2008). Research has been focused primarily on flow structure (Rhoads and Kenworthy, 1998), including secondary currents (Riley and Rhoads, 2012) and turbulence (De Serres et al., 1999). To a lesser extent, bed morphology has also been the object of various field studies (Rhoads et al., 2009; Riley and Rhoads, 2012), together with particle-tracking studies to understand the sediment trajectories (Best, 1988; Roy and Bergeron, 1990). Nevertheless, actual sediment transport measurements in river confluences are very limited (Rhoads, 1996; Boyer et al., 2006) and are lacking for large gravel-bed rivers.

Bedload transport within confluences has been identified as a big gap and a fertile ground for research (Best and Rhoads, 2008). In addition, this confluence is a medium to large gravel-bed river system with a bankfull discharge of about 1000 m^3/s. Five connected topics are treated: (i) the balance between tributary and main river contributions to total bedload, (ii) the spatial distribution of bedload across the river channel, (iii) the grain-size distribution of bedload in comparison with the river grain sizes, (iv) the performance of predictors that compute bedload by grain-size fractions, and (v) the conditions at which bedload is transported, either at-capacity or below-capacity or, in other words, the conditions at which it is controlled either by capacity or by supply. These research objectives were compatible with the request of quantifying the total bedload arriving at the planned facility. The request provided an opportunity to better understand the bedload transport, which serves as a link between confluence flow and bed morphology at the confluence, even with limited hydrodynamic measurements. The need to include different mechanisms to account for the field results in the discussion may be a novel aspect.

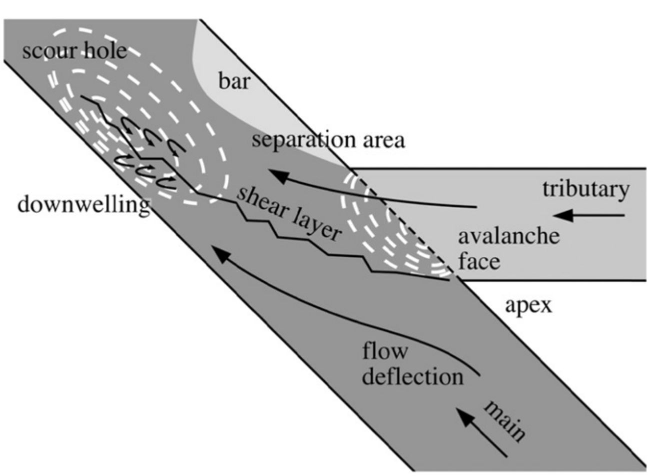

Fig. 2. Sketch of hydro- and morphodynamic features observed in a river confluence. Source: adapted from the literature.

For the purpose of this paper, two minor remarks are retained from the literature review: (i) the bed discordance reduces the main river flow deflection (Biron et al., 1996) and (ii) a high tributary over main river discharge ratio narrows the scour hole and pushes it toward the main river bed, hampering the entry of much of the bedload (Best, 1988; Rhoads et al., 2009).

2. Description of the study area

Ninety-five kilometres before flowing into the ocean, at an elevation of 105 m above sea level (asl), two large streams join: the Toltén itself (*i.e.*, the main river), naturally regulated by Lake Villarrica, and the tributary Allipén, which runs mostly unregulated. The drainage areas at the confluence are 2500 km^2 for the unregulated tributary and 3200 km^2 for the regulated main river (Fig. 1). The confluence is located in a flat alluvial area dominated by a single rock outcrop that protrudes into the river from its left bank shortly downstream of the confluence (Fig. 3). The outcrop is the only conspicuous geological controlling factor on the stream planform, and it forces the river to turn sharply to the right. The rock outcrop offers a solid left buttress for the planned weir. In the study area the tributary has a wandering planform, while the