Evaluation of image velocimetry for the quantification of discharge and characterization of the flow in the Pilcomayo River with acoustic profilers

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Introduction

The Pilcomayo River Basin covers an area of approximately 290,000 km^2 in Argentina, Bolivia and Paraguay and integrates the large Plata river basin. Although the Pilcomayo River is a mountain river in the upper basin, it becomes a plain river when it leaves the Andes near Villa Montes town, Bolivia. The river is 1,000 km long, and extends from approximately between 19 ° and 26 ° Lat. South and between 57 ° and 67 ° Long. West. Downstream Villa Montes, as a result of very low slopes, there are overflows points that flood large areas of land during flood times. One of the main objectives in the agreements signed by the three countries is the quantification of the water resource in the system, and its analysis of spatial and temporal evolution.

The objective mentioned before are reflected, for example, in the agreements between Paraguay and Argentina (Creation of the Trinational Commission for the Development of the Pilcomayo River Basin and the Binational Administrative Commission of the Lower Basin of the Pilcomayo River) in which both countries have incorporated the principle established in the Treaty of the Plata River Basin regarding the multiple and equitable use of water courses.

To advance on the planned research, and to fulfill the existing agreements, an accurate quantification of discharge was necessary. Therefore, state of the art techniques were selected both to verify

the accuracy of the traditional techniques used today (with a current meter from a cableway), and to obtain a detailed characterization of the flows in space and time.

The simplicity of Doppler technology has turned into a universal practice in river hydraulics. In addition, it provides a high temporal and spatial resolution of the flow field by acquiring information that is impossible to obtain through conventional methods.

For field measurements the acoustic instrument commonly used is the ADCP (Acoustic Doppler Current Profiler). Although the ADCP technique is very efficient to quantify drained flows, to characterize flow fields, and to estimate solid sediment discharges in suspension, there were problems when it was applied to the Pilcomayo River. The reason why problems arose was the high content of suspended sediments that attenuate acoustic signals significantly. In addition, under flood conditions, discharge and floating debris in the river jeopardize both, operators and instruments. Therefore, in this chapter another technique is evaluated: the remote measurement technique of image velocimetry.

Large Scale Particle Image Velocimetry

Particle Imaging Velocimetry (PIV) has been widely used in hydraulics for more than 30 years in laboratory experiments (Adrian, 1984, 1991, 2005). Technological advances at the level of image recording (digital cameras with increasing the resolution of the sensors, and image frequency), as well as the level of computing (faster calculations, more memory) allows the study of increasingly complex flows and rapids (Willert and Gharib 1991; Malik and Dracos 1993; Raffel et al. 2007; Adrian and Westerweel 2011; Nezu and Sanjou 2011; Tien et al. 2013). The principle of the method is to extract sub-regions (interrogation windows) from a pair of images, and apply a cross-correlation between them to derive the most likely displacement of particles in the interrogation windows. Basically, cross-correlation is a statistical pattern search technique that attempts

to find the displacement of particle patterns between a window *A* and a window *B*, where *A* and *B* are consecutive interrogation windows (see Figure 41). Therefore, the discrete cross-correlation function measures conformity between interrogation window *A* and interrogation window *B* for a given offset (Raffel et al., 2007). The location of the intensity peak in the resulting correlation matrix C gives the most likely displacement of the particles from *A* to *B* (Huang et al., 1997).

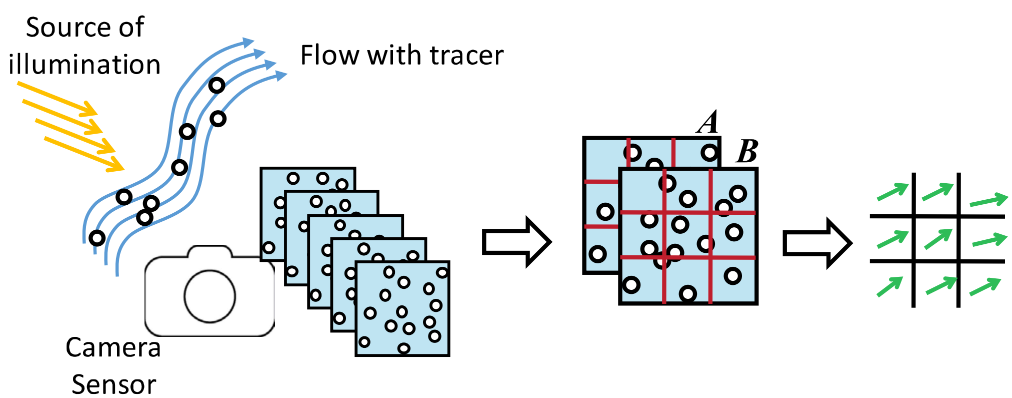

Figure 41.- PIV operating principle. The three essential elements are a source of illumination, a plotter representative of the measured flow, and a camera sensor. The images are divided into question windows.

Since the 1980s, several researchers have attempted to adapt PIV techniques to characterize larger scales than laboratory scales. The former include field measurements, and are called Large-Scale Particle Image Velocimetry (LSPIV) (Le Coz et al., 2014; Creutin et al., 2003; Detert and Weitbrecht, 2015; Fujita et al., 1998; Gunawan et al., 2012; Muste et al., 2008; Patalano et al., 2017b). Mainly LSPIV has been used for the analysis of the superficial velocity of the water, and the estimation of the discharge in rivers. The main difference between PIV (small scale) and LSPIV (large scale) are the flow of interest scales. PIV and LSPIV also differ in the complexities associated with large-scale field measurements such as variable lighting, and limited accessibility to orthogonal camera views. Oblique camera views require precise geometric rectification of images or velocity results to overcome the appreciable distortions produced by the camera viewing angle through a minimum of four known control points (CP) (Figure 42).

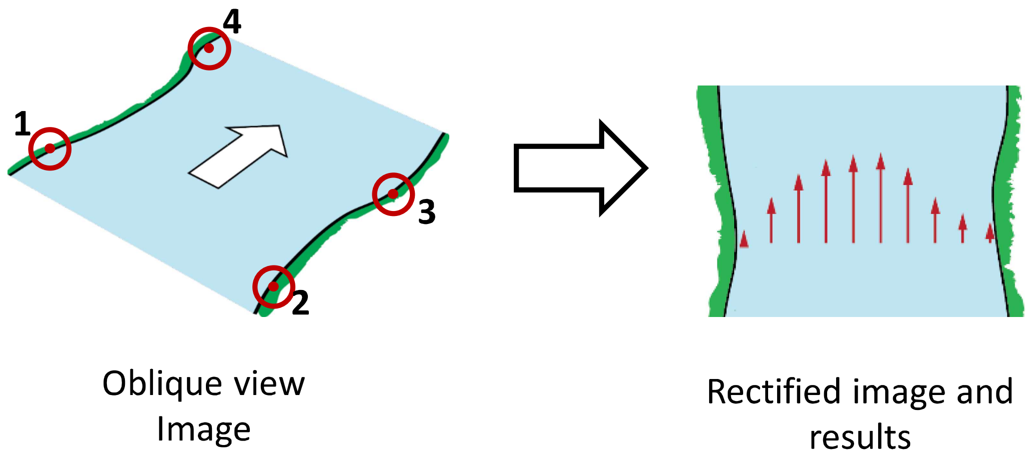

Figure 42.- Example of rectification of a river section when the camera view is oblique.

RIVeR is an application developed by the authors of this chapter at the National University of Córdoba, Argentina (Patalano et al., 2017b). This application is free and built in Matlab®. RIVeR has been developed in order to provide an experimental characterization of large-scale superficial water flows in rivers, artificial canals (for example, irrigation, treatment plants and others) and / or large - hydraulic physical models. The aforementioned characterization includes the determination of flow velocities and discharge estimation. RIVeR allows the rectification of the results of PIV processing executed with PIVlab (Thielicke and Stamhuis, 2014). These two applications will be both used in this chapter in the evaluation of the LSPIV technique for discharge quantification and flow characterization in the Pilcomayo River.

Methodology: experimental techniques and devices

The experimental evaluation was carried out on February 20, 2014 in the "Villa Montes" gauging section located in the town of the same name in Bolivia (Figure 43), in the department of Tarija at 21.26 ° Lat. South and 63.50 ° Long. West at 407 meters above sea level and operated by the National Service of Meteorology and

Hydrology of Bolivia (SENAMHI) in accordance with the Executive Management of the Tri-National Commission for the development of the Pilcomayo River Basin (DE CTN), Szupiani et al (2014). It is a stable section at the bottom of the Andes where its sediments are still thick, and it is located a few kilometers upstream from the beginning of the lower basin. The importance of this gauging station is that it provides values of incoming liquid and solid flows to the lower basin. In this station, records of average daily discharge have been kept since August 1976, and records of sediments in suspension and granulometry since 1981. The average annual flow is 237 m^3/s, and the recorded peak of floods have reached 6,500 m^3/s. Prior to the use of the new technologies, liquid and solid gap measurements were created with conventional techniques (current-meter and suspended sediment samplers). The importance of precise knowledge of the liquid and solid discharge through this section becomes evident particularly when calculating the balance of liquid and solid discharges between Villa Montes and Mission La Paz, which is located 190 km downstream. In fact, overflows can probably occur on both margins of this section.

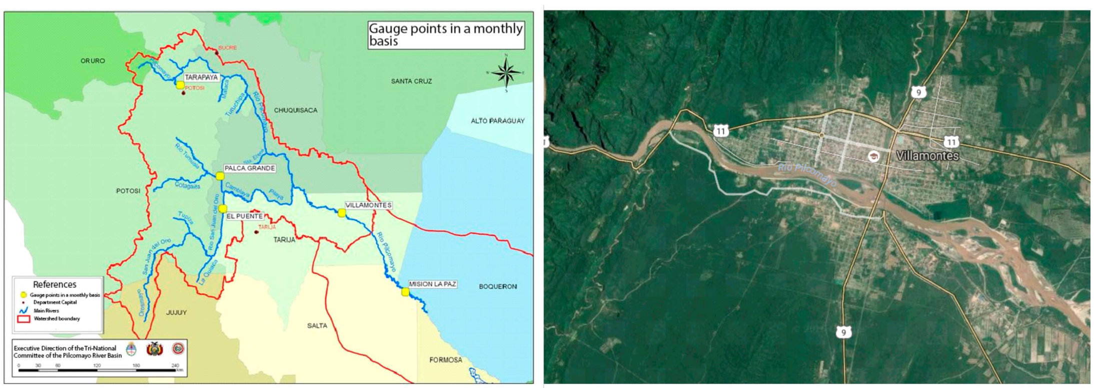

Figure 43.- Location of the gauging cross-section.

Figure 44 shows the measurement section examined with different experimental techniques. This section of the river coincides with the Villa Montes gauging section in Bolivia, which includes a cableway system to travel across the river section. Although this chapter focuses on the evaluation of image based velocimetry, Doppler Acoustic Current Profilers (ADCP) technology was also used. This

methodology makes use of different acoustic frequencies that allow to register spatial and temporal configurations. The instruments used were the following: a "River Surveyour S5", manufactured by the company YSI / Sontek and two "Workhorse Rio Grande" manufactured by the Teledyne RD Instruments Company. The first ADCP was used for shallow water with an acoustic frequency of 3MHz. The other two instruments have similar hardware although they work at different frequencies, (600 kHz and 1200 kHz). This variety of instruments allow a better characterization of both, discharge and sediment transport.

Figure 44.- Cross-section of the Pilcomayo river in Villa Montes, Bolivia. The cable-way can be seen in the center.

For the implementation of, a SONY camera, model WX300 was used. The camera was placed on a crane on top of a tripod, so the camera was high enough to focus on the section of interest, and it was remotely controlled. The assumption that visible patterns on the water surface and the river water travel at the same velocity constitutes the working hypothesis of this investigation. Therefore, the visible patterns can be used as tracers.

The entire experimental system described was located on the left bank of the river (Figure 45). The resolution of the images in "video" mode is 1920 x 1080 pixels, and the rate at which the images

are acquired is 30 images or frames per second (fps). A four minutes movie of the section of interest was recorded at this rate. In order to have a measurable displacement of patterns in the images, it was necessary to reduce the rate to a quarter. Consequently, the new time step between frames was 133.47 ms. This procedure was carried out by the use of RIVeR software.

In PIVlab, the algorithm called Fast Fourier Transform (FFT) was used. It allows cross-correlation in the frequency domain. Interrogation windows of 128, and then 64 pixels were used to obtain the displacement field of the entire section of the river. Figure 45 shows the result obtained after the application of this algorithm in [pixel / image]. This result is not yet representative of the surface velocity field since the displacements between images are distorted as a consequence of the obliqueness of the line of sight. An arbitrary distance in meters does not represent the same amount of pixels according to their location on the image. Therefore, after processing, it is necessary to rectify the results in order to obtain the real velocity field in [m/s] of the section of interest.

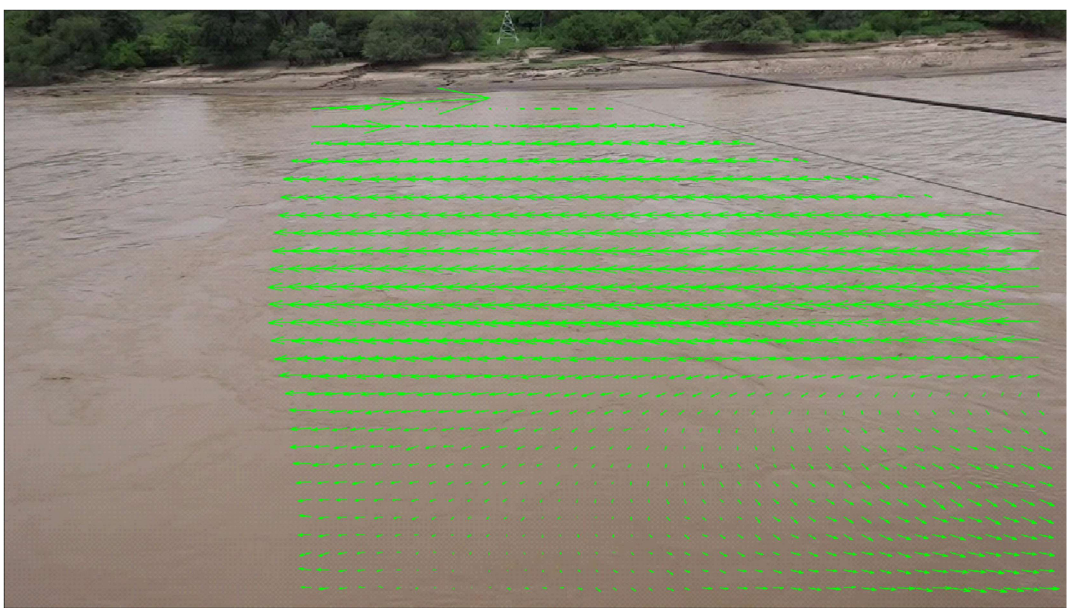

Figure 45.- Average displacement field in [pix / image pair] obtained from PIV processing in PIVlab software.

In RIVeR, to rectify the PIV results, the homography was used as a projective transformation for which it is necessary to know the coordinates of four Control Points (PC) in both systems: Image in [pixel] and Real World [m]. In the Real World four PCs need to be in the same plane to solve the homography. The geographic coordinates of the four PCs were surveyed using the GPS of the River Surveyour S5 ADCP (Figure 46). Once the velocity field was rectified, the cross section was determined, and the superficial transverse velocity profile was discretized into 32 values, 3 m spaced (Figure 46). To estimate the discharge, the "mid-section" method was used with the superficial velocity profile, and the bathymetry, which was measured with the ADCP "Workhorse Río Grande" of 600 kHz.

The estimated flow rate is multiplied by a coefficient α (Cheng et al., 2004) that characterizes the relationship between the mean and the superficial velocities of the section measured (α = 0.85. A logarithmic vertical velocity profile was assumed).

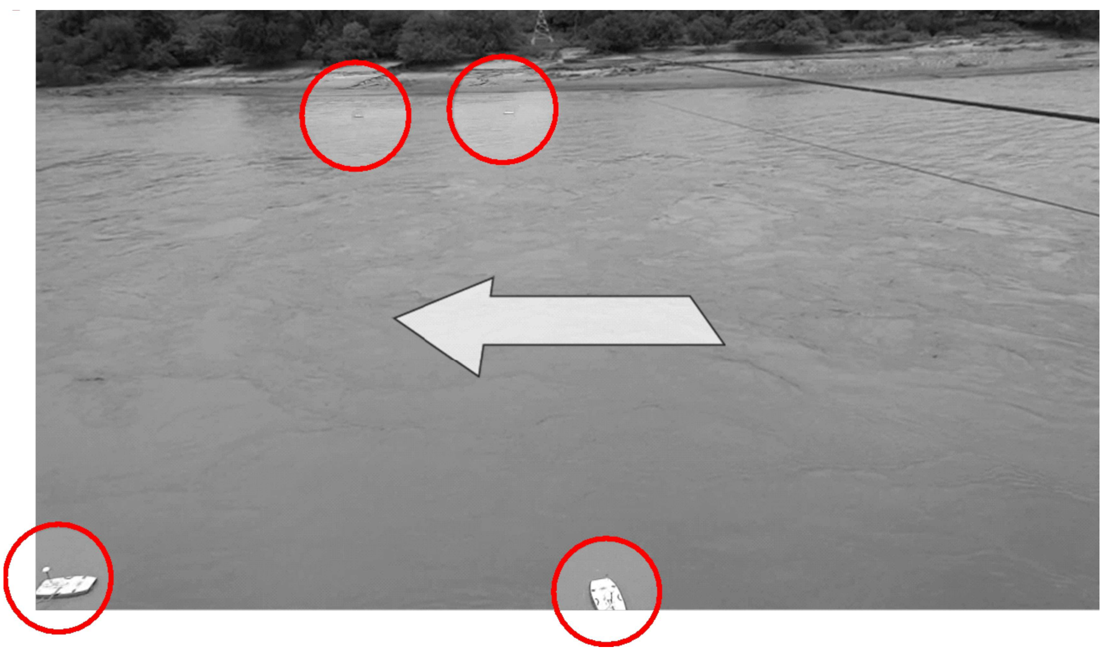

Figure 46.- Image taken with the digital camera from the left bank of the river. The cableway can be seen in the upper right corner of the photo. The location of the four PCs surveyed with the River Surveyour S5 ADCP are encircled. The figure is composed of four photographs, which correspond to the positions of the ADCP.

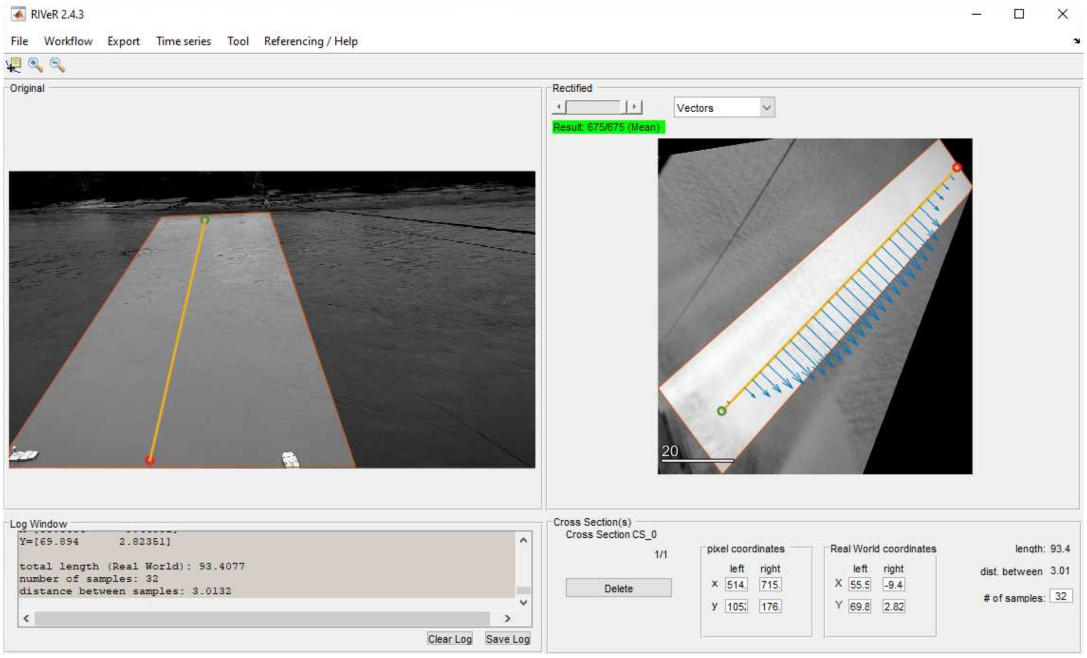

Figure 47.- Graphical user interface of RIVeR 2.4.3. On the left, there is an unrectified image of the working cross section. On the right, the rectified velocity profile in the same section.

Results analysis

A good agreement is observed between the values retrieved by the different techniques, and it should be noticed that the LSPIV technique successfully reproduced the superficial velocity field. This section presents the positive and negative aspects of the implementation technologies and methodologies applied in this work.

The RDI Profilers “Workhorse Río Grande” of both frequencies (600 kHz and 1,200 kHz) proved to be suitable to measure the discharge, velocity profile and bed morphology in the river section under study. However, the configuration parameters of these instruments were adjusted to extend their measuring ranges since the suspended sediments caused great attenuation of the signal.

The 600 kHz ADCP showed greater robustness (no loss of speed data or background recording) although its spatial resolution is lower than profilers with higher acoustic frequency. The “River Surveyour S5” shallow water ADCP profiler characterized only the velocity field of the region near the free surface (2.5m) along the entire cross section,

and did not record velocity values at greater depths because the high sediment load attenuated its high frequency signal.

Figure 48 shows a comparison between cross-sectional velocity profiles measured with the different techniques in addition to the current meter. This plot compares the velocity data recorded by each technique and / or instrument in the region near the free surface. The ADCP cells selected were the closest to the surface.For the RDI Profilers "Workhorse Río Grande" of frequencies (600 kHz and 1,200 kHz) the data nearest to the free surface were recorded at depths of 1.1m and 0.92m while for the ADCP "River Surveyour S5", velocity values were recorded at a depth of 0.15m (higher acoustic frequency, smaller cell size used and smaller depth to the first cell with valid velocity data).

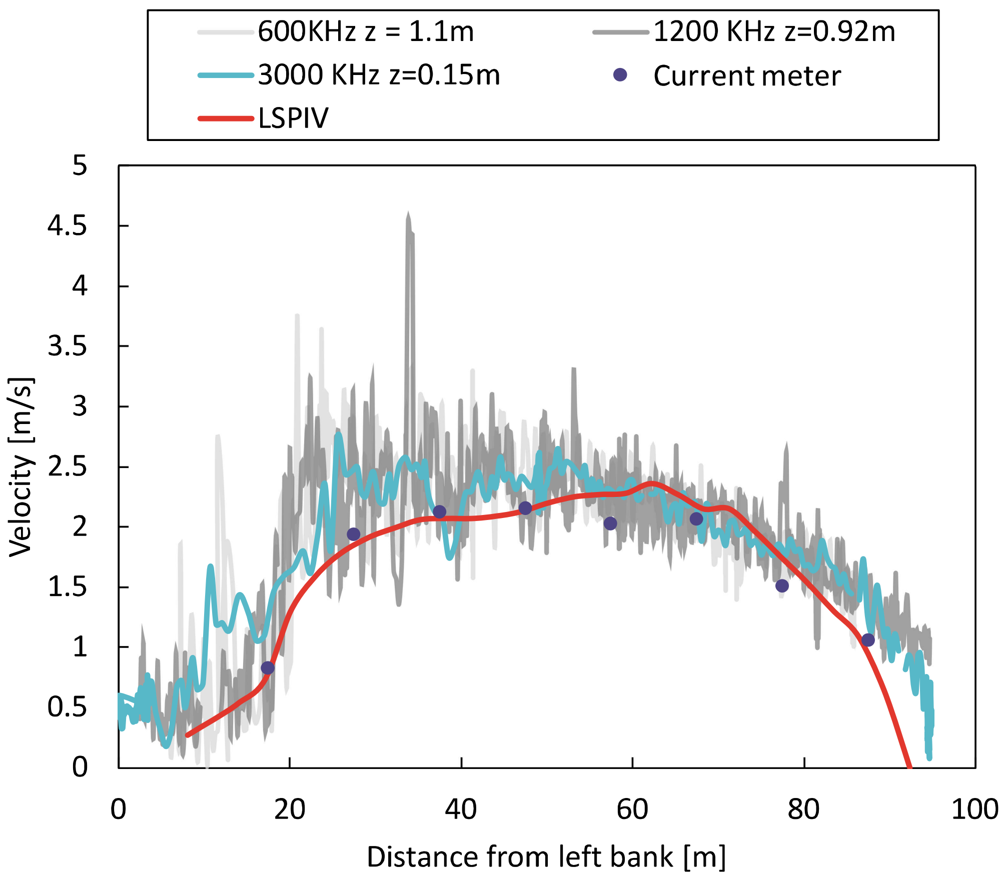

Figure 48.- Comparison between velocity profiles measured across the river in the region near the free surface with different techniques.

Figure 49 shows a comparison between the bathymetry of the cross section surveyed during the discharge measurement with the different techniques. In the graph also includes the depth values surveyed with the current meter. It is worth to notice that the ADCP "Workhorse Río Grande" of 600 kHz acoustic frequency shows a continuous data registration of the river depth in contrast to the other profilers.

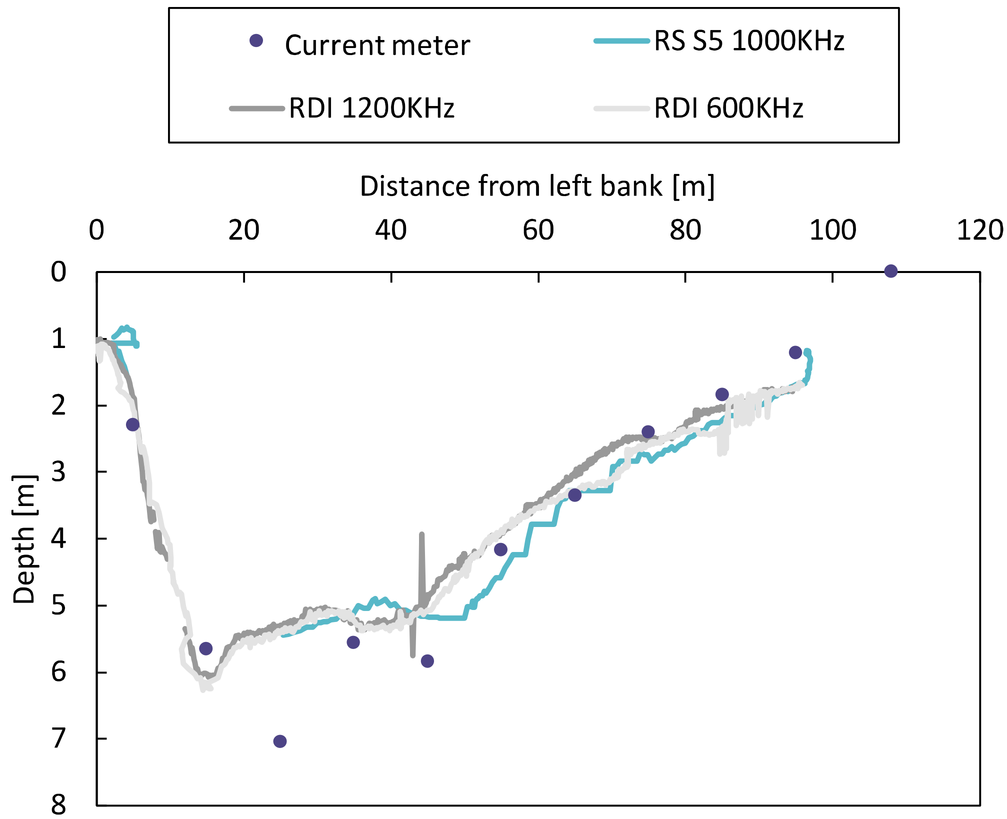

Figure 49.- Comparison between the bathymetry of the cross-section measured with different techniques

Regarding the discharge, it is interesting to compare the values obtained with all the techniques applied in this work. The conventional technique (current meter from the cableway) gave a value of 628m^3/s. Instead, the values obtained from the "Workhorse Río Grande" ADCPs was 659 m^3/s (4.9% difference with current meter), and 640 m^3/s (1.9% difference with current meter) for acoustic frequencies of 600KHz and 1200KHz. Based on the cross-

sectional profile of superficial velocities measured with LSPIV and the bathymetry measured with ADCP, the discharge value obtained is 648 m^3/s (3.1% with the value adjusted with the current meter).

Conclusions

On one hand, river flow superficial velocities were successfully obtained with the LSPIV technique. Therefore, the LSPIV technique has a good potential for the estimation of flow in the Pilcomayo River and any other river system. The only extra requirement is precise knowledge of the bathymetry in the river section under study.

In this LSPIV evaluation, control points such as bathymetry have been surveyed with the acoustic current profilers since the LSPIV recording was one time case study. In the future, a fixed LSPIV station could be installed in this section (Patalano et al., 2017a). This is the reason why, it will be necessary to survey (only once) both, a higher amount of control points in space, and the topography of the cross section extended to the margins.

On the other hand, the acoustic profilers evaluated have positive and negative aspects. Although the ADCP profiler "River Surveyour S5" has the highest spatial resolution (cells up to 2cm), it can only record the velocity field of the region near the free surface (2.5m) along the entire cross section. The RDI Profilers "Workhorse Río Grande" of both frequencies (600 kHz and 1200 kHz) proved to be suitable to evaluate the flow rate, velocity profile and background morphology. Since there was high signal attenuation, instrument parameter settings had to be made to extend the measurement ranges. The 600 kHz ADCP gave evidence of greater robustness since there were neither loss of speed data nor background recording although its spatial resolution is lower than profilers with higher acoustic frequency. The flow rate recorded with both ADCP RDI differs by less than 5% compared to the traditional method, but the 1200 kHz profiler does not record velocity values at greater depths as a result of its higher acoustic frequency.

Despite the fact that the acoustic profilers are able to measure the flow discharge in the Pilcomayo River, they require highly skilled

users to set their parameters to compensate for the influence of the sediment concentration of the river.

In conclusion, the LSPIV technique resulted in a good alternative to acoustic profilers or current meter for the estimation of the Pilcomayo River discharge since its use makes it unnecessary to risk human life on a cableway. Moreover, this technique appears to be simpler to implement. It is recommended to install a fixed station that would allow continuous flow monitoring in this river section. Furthermore, the implementation of LSPIV from a drone is also suggested for spontaneous measurements that would be even simpler than those measurements from a river bank. Instead of four accurate CPs, with a drone it is necessary to measure only a single distance which simplifies the image/results transformation.

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