Ecosistemas Y Recursos Agropecuarios

Natural discharge measures from bridges with piers

Aforo de corrientes naturales desde puentes pilotados

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ABSTRACT. Measuring a river discharge from bridges with piers has been questioned. However, here, it is shown that now it is feasible to do it without losing accuracy using acoustic Doppler equipment. The objectives of this work were to analyze the possibility of measuring from bridges with piers with acoustic Doppler equipment and find if there is a difference between measuring upstream or downstream of the bridge. The discharge rate, the plain view, and cross-section hydrodynamics were evaluated and compared analytically and graphically in each section. Also, the intensity of the suspended sediments in each area was assessed. The results showed that the difference between measuring upstream or downstream of a bridge is less than 1.5%. Hydrodynamically, a difference in flow direction was obtained due to the curvature of the river and the bridge's piers, but it does not affect the flow discharge measurement.
Key words: Flow field measurements, acoustic Doppler profiler, hydrodynamic fields, beam intensity.

RESUMEN. Aforar el caudal de un río desde puentes pilotados ha sido cuestionado; pero aquí se demuestra que ahora es factible hacerlo sin perder precisión utilizando equipos acústicos Doppler. Los objetivos de este trabajo fueron analizar la posibilidad de medir con equipos acústicos Doppler desde puentes pilotados y encontrar si existía diferencia entre medir aguas arriba o aguas abajo del puente. El caudal, la hidrodinámica en planta y transversal, se evaluaron y compararon analítica y gráficamente en cada sección. Asimismo, se evaluó la intensidad de transporte de los sedimentos en suspensión. Los resultados mostraron que la diferencia entre medir aguas arriba o aguas abajo de un puente es inferior al 1.5%. Hidrodinámicamente se obtuvo una diferencia en la dirección del flujo debido a la curvatura del río y las pilas del puente, pero esta no afecta la medición de la descarga del flujo.
Palabras clave: Aforo de corrientes en campo, perfilador acústico Doppler, campos hidrodinámicos, intensidad de sedimentos.

INTRODUCTION

The study of currents is key to understand the environment since it is in there where nutrients and pollutants that affect the fauna and flora of the riverbed and its banks are transported (Gore and Banning 2017, Bodmer *et al.* 2018, Bekri *et al.* 2019). There are different techniques to measure discharge in natural currents; details can be found in Gore and Banning (2017). Each method has well-defined procedures, so the choice depends on the characteristics of the river to be measured -wide, depth, discharge-. Applying a method out of its range can produce errors in the measurement. A particular case is measuring discharge from bridges (Turnipseed and Sauer 2010). Bridges are structures that allow communication between two regions; therefore, they are easily accessible and ideal for measuring the flow discharge from them. One of the main recommendations for measure from bridges is that they are of a single span (BSI 2007); which means they must not have piers or obstructions in their structure (Gore and Banning 2017). However, sometimes it is not common to find this type of structure due to the width of the rivers. Thus, when measuring over a bridge with piers, usually upstream, the flow is smoother; while downstream, it is altered by the effect of the piers that support the bridge (Turnipseed and Sauer 2010).

The ideal way would be to measure from the upstream side; however, from a practical point of view, it is not convenient because the flow can carry the measuring instruments under the bridge. Therefore, this paper also analyzes the difference between measuring upstream and downstream of the bridge. Given this fact and with the advancement of technology, acoustic Doppler current profilers (ADCP) have played an essential role in measuring natural currents (Priego-Hernández *et al.* 2018, Mercier *et al.* 2021). The ADCP are measuring instruments that apply the physical Doppler principle. They emit an ultrasonic sound on the water column that makes the suspended particles transported by it to vibrate. At low frequencies - less than 25 kHz - the amplitude of this vibration is practically the same as that of the medium; still, as it increases, it becomes significant.

At frequencies greater than 25 kHz, the vibration remains stationary, allowing measuring the flow velocity (Vogt and Neubauer 1976). Details of the operation of the ADCP can be consulted at Priego-Hernández *et al.* (2018).

In addition to the velocities of the suspended particles, the return beam also measures its intensity, which can be transformed into suspended sediment load (Latosinski *et al.* 2014, Dominguez-Ruben *et al.* 2020). Their efficiency, speed, and quality in measuring the flow discharge are higher than traditional devices. Also, ADCPs measure the three-dimensional velocity fields and sediment intensity, which allows an understanding of river systems' hydrodynamic and sedimentological characteristics (Parsons *et al.* 2013, Dominguez-Ruben *et al.* 2020). Other studies (Nystrom *et al.* 2002, Guerrero and Lamberti 2011) have reported an ADCP velocity measurement error of the order of $\pm$ 1 cms^{-1}.

This paper used an ADCP to study the capacity of such a device to measure flow discharge from bridges. The objectives were to analyze the possibility of measuring with ADCP from piloted bridges and find if there is a difference between measuring upstream or downstream of the bridge. An evaluation and comparison of the flow discharge, the hydrodynamics, and the intensity of the suspended sediments -analytically and graphically-were made. The study area, the characteristics of the equipment used, the data processing, and the analyzes carried out are described in the next part.

MATERIALS AND METHODS

Study zone

A bridge with six tubular piers was selected; its length and width are 72 m and 7 m, respectively. The pier width is 0.30m. The bridge (Figure 1) is located over the Belen River in Nacajuca, Tabasco, Mexico (coordinates 2012822.90 m N, 505181.84 m E, in zone 15 N). The Belen River is a plain river with a subcritical regime; a mean slope of 0.00031, and an average annual flow of 65.50 m^3s^{-1}, it is considered a clay river.
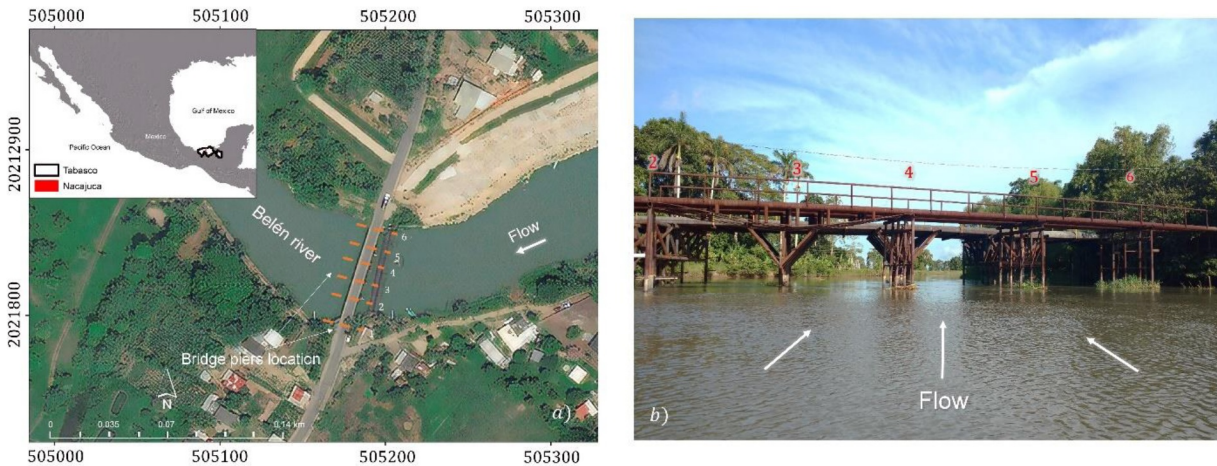
Figure 1. Bridge over the Belen River, Nacajuca, Tabasco Mexico. a) Location and plan view and b) Panoramic of the bridge.

Measurements with ADCP

Two cross-sections for measurement were selected, the first 35 m upstream and the second 12 m downstream of the bridge. Each section was measured with the ADCP 10 times. The ADCP used was the Teledyne RDI RiverRay, with a frequency of 600 kHz. We followed the recommendations by Muste *et al* (2004a,b); the ADCP was mounted on a boat and coupled to a global positioning system (GPS). The GPS controlled the measurement repetitions made in each cross-section (Huang 2019). To ensure that the velocity vectors were oriented in the correct direction, the ADCP had to be calibrated before the measurements; the procedure consisted of calibrating the internal compass of the equipment through circular movements of the same on its horizontal plane in a clockwise direction (Simpson and Oltmann 1993). Another critical data is the magnetic declination since it is essential to orient the measured velocity vectors (Mueller 2018). This step is often skipped due to a lack of experience of the operator. This data is entered in the initial configuration and depends on the geographic coordinates of the study site. A recommendation to obtain it is from the website of the British Geological Survey (BGS 2020); this data has units of degrees in an easterly direction.

The flow discharges

The upstream and downstream flow discharge datasets were obtained directly from the Winriver II software -this software is supplied by the manufacturer-. Winriver estimates the discharge applying the power method and doesn't need correction (Teledyne 2018).

In each measurement section, 10 repetitions were made to determine: the instantaneous flow discharge Q [$m^3 s^{-1}$]; the average flow discharge $\hat{Q}$ [$m^3 s^{-1}$], the standard deviation of the average flow discharge $\hat{Q}_\sigma$ [$m^3 s^{-1}$], the section distance D [m], the average section distance $\hat{D}$ [m], and the standard deviation of average section distance $\hat{D}_\sigma$ [m]. The relative uncertainty was determined as the quotient between the absolute uncertainty (standard deviation) and the observed magnitude. The significance of the error concerning the observed magnitude is an indicator of the quality of the measurements.

Hydrodynamic data processing

It was carried out using the free software Velocity Mapping Toolbox VMT (Parsons *et al*. 2013). VMT can directly read the file generated by Winriver II. VMT performs a filtering process of the measured data, projects each transect in an average section, and generates uniformly distributed velocity fields, facilitating its analysis. This VMT file can be exported to an Excel file to be manipulated. An example of the original file obtained from VMT is shown in Table 1. The file has 9 columns: the first corresponds to

Table 1. Excel data file generated by VMT software.

Timestamp	UTM Easting (WGS84) [m]	UTM Northing (WGS84) [m]	Depth from surface [m]	Distance from Left Bank [m]	East Velocity [cms^{-1}]	North Velocity [cms^{-1}]	Vertical Velocity [cms^{-1}]	Velocity Magnitude [cms^{-1}]
8:30:06	505160.3	2012802.3	0.3	0.0	-25.7	-29.4	-3.9	39.2
8:30:06	505160.3	2012802.3	0.4	0.0	-15.3	-22.0	0.1	26.8
8:30:06	505160.3	2012802.3	0.4	0.0	-8.4	-18.2	-3.0	20.2

the time at which the measurement is performed; the second and third correspond to the geographical position in UTM coordinates; the fourth and fifth are the depth [*m*] and the distance [*m*] at which each velocity vector was measured, respectively; the sixth, seventh and eighth are the components of velocity [cms^{-1}] in the east, north, and vertical directions (x, y, z); and finally, column 9 is the magnitude of the velocity vector [cms^{-1}]. VMT generates the components of the velocity vector in cms^{-1}; therefore, for comparison purposes, it is recommended to convert to ms^{-1}.

Visualization of hydrodynamic and sediment intensity data

The visualization helps to understand the behavior of the flows upstream and downstream of the bridge. In this work, the hydrodynamic and sediment intensity fields were plotted using Tecplot 360 Software. To construct each graph, a .dat file was generated from the Excel file obtained by VMT. The structure of this file is simple; in the first row, the name of the file: Title = "file name"; In the second, we defined the plotted variables: Variables = "X$_1$," "X$_2$," "V$_1$," "V$_2$"; where X$_1$ and X$_2$ are the positions, and V$_1$ and V$_2$ are the measured variables. These data must be separated in spaces and by rows. By this procedure is possible to plot the following characteristics (Table 2).

RESULTS AND DISCUSSION

The flow discharges

The measurements made upstream and downstream were presented. A statistical analysis of the results (Table 3): the flow discharge (Q), the length of the cross-section (D), and the standard deviation associated with the measurements were reported.

From Table 3 is found that the difference between the average flow measured at the upstream and downstream sections is 1.428 m^3s^{-1}. The percentage of errors in the measurement ranges between 1.38 and 1.63%. The World Meteorological Organization (WMO 2010) establish that the bridge pier area has to be removed from the measurement; and Gore and Banning (2017) said that it is only possible to do it on bridges without piers. However, in this work was showed that it is possible to do it without compromising the quality of the measurements. The key is the measurement equipment; acoustic Doppler equipment should be used in these cases.

Plain view velocities

Figure 2a shows the plain view velocities upstream and downstream of the bridge. The magnitudes of the flow velocities are plotted in Figure 2b; the curve S_1, corresponds to the measured upstream section; and curve S_2 to the downstream. It is observed that the plain view velocities for the upstream section (S_1), velocities keep uniformity in most of the whole sections (red), while low velocities are observed in the banks (green). For the velocities in the downstream section (S_2), the magnitudes and trajectories of the velocities show a variation in their direction. This is due to two effects: the bridge's piers and the other due to the channel's curve. This behavior shows the impact of the piers and the curve on velocities and identifies erosion and deposition areas downstream. In the upstream case, this behavior is not appreciated.

Cross-section view of velocities

The velocity magnitudes (range of colors) and the cross-section vectors measured at upstream (Figure 3a) and downstream (Figure 3b) sections were plotted. Also, the upstream (Figure 3c) and downstream (Figure 3d) recirculation zones were

Table 2. The flow characteristics. (X), (Y) the north and east ADCP positions.(UTM coordinate system); S, the ADCP cross-section distance (m); H, the depth at which each velocity vector was measured (m); (U,V,W), are the main, transverse and vertical components of the velocity vector (ms^{-1}); and (I), is the intensities of the suspended sediments measured by the beam return (dB).

Flow characteristics	Position	Variable plotted
Plan view velocities	X, Y	U, V
Cross-secction velocities	S, H	U, W
Suspended sediment intensity	S, H	I

Table 3. Average flow and distance. Q, flow discharge ($m^3 s^{-1}$); D, section distance (m); $\hat{D}$ average section distance (m); $\hat{D}_\sigma$, the standard deviation of average section distance (m). $\hat{Q}$, average flow discharge ($m^3 s^{-1}$); $\hat{Q}_\sigma$, the standard deviation of the average flow discharge ($m^3 s^{-1}$).

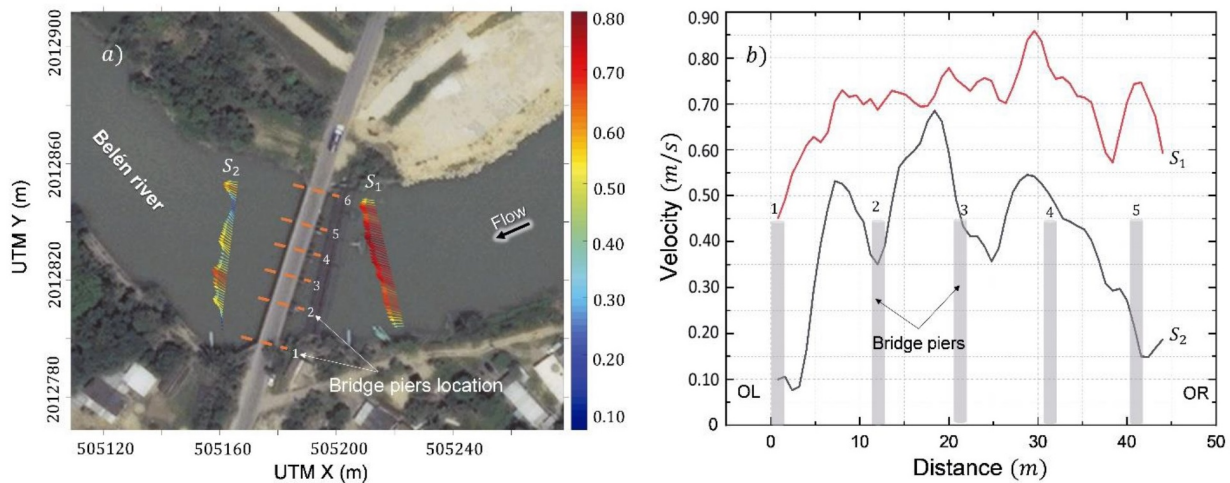| N	Upstream section						Downstream section					
	Q	D	$\hat{D}$	$\hat{D}_\sigma$	$\hat{Q}$	$\hat{Q}_\sigma$	Q	D	$\hat{D}$	$\hat{D}_\sigma$	$\hat{Q}$	$\hat{Q}_\sigma$
1	117.77	48.52					116.50	50.20				
2	117.06	47.84					123.04	58.77				
3	119.87	49.30					120.13	53.72				
4	115.38	47.20					118.30	52.03				
5	118.51	52.08	49.061	1.628	118.001	1.642	117.24	51.15	53.389	2.401	119.429	1.957
6	116.74	47.52					121.40	55.42				
7	117.27	48.55					118.24	52.20				
8	120.24	51.25					119.25	53.10				
9	117.02	48.18					120.20	53.80				
10	120.15	50.17					119.98	53.50				

Figure 2. a) Plain view velocities; b) Magnitude of the average velocity in upstream and downstream cross-sections.

drawn. Figures 3a and 3c (upstream) show homogeneous velocities at the center of the channel. Meanwhile, Figures 3b and 3d (downstream) show the recirculation effects caused by the piers and the channel's curvature (Priego-Hernández and Rivera-Trejo 2016). The recirculation generated between the piers, as well as the erosion on the left bank, are due to the curvature of the channel (red arrows); however, on the right bank (between 40 and 50 m from the section), the erosion developed is only due to the piers.

Suspended sediment intensity

Figure 3e-f shows the suspended sediment's intensity. The measurement units are decibels (dB);
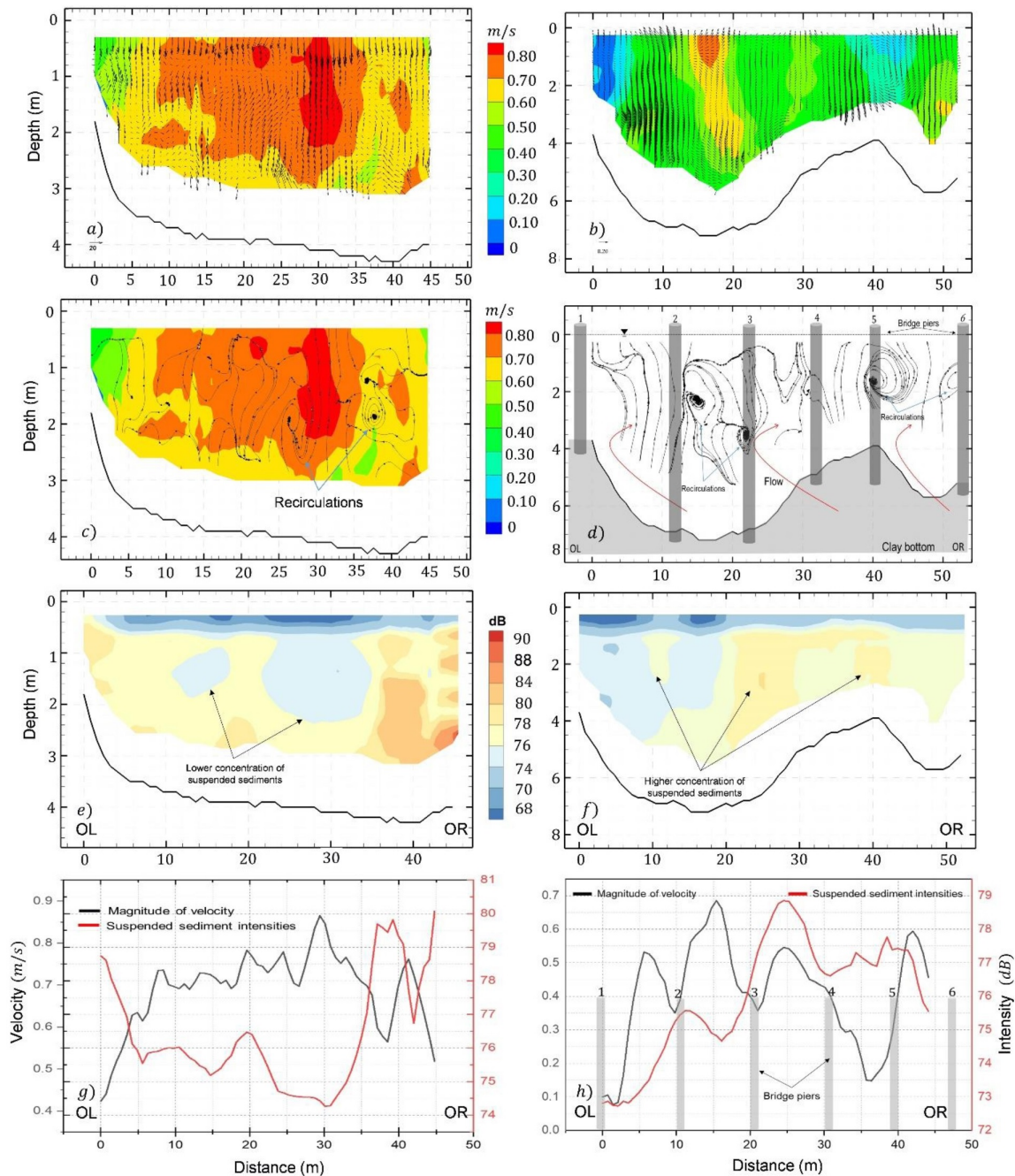
Figure 3. Hydrodynamic fields: a) upstream and b) downstream; and recirculation zones, c) upstream and d) downstream. Suspended sediment intensity: e) upstream and f) downstream; and intensity and velocity relationship: g) upstream h) downstream.

the interpretation is that higher values equal higher sediment concentration circulating through the cross-sectional area. In Figure 3e (upstream), the lowest concentration of sediments (blue) is found in the cen-

ter of the channel. At the same time, the highest is skewed towards the right bank (red).

On the other hand, downstream, three zones with different sediment concentrations are observed

(Figure 3f). Low concentrations are close to the surface (blue), medium concentrations in the banks (ivory), and higher concentrations at the center of the channel (light yellow). There is a relationship between velocities (Figures 3a and 3b) and intensities (Figures 3e and 3f); low-velocity zones load higher sediment concentration, while higher velocity zones load lower sediment concentration. This is explained because, at higher velocities, there is a more significant amount of water than sediment. In contrast, there is a more significant amount of sediments at low velocities than water.

Figures 3g and 3h plotted the velocity vs. the sediment intensity upstream and downstream of the bridge, respectively. Upstream, the sediment intensities decrease in areas whit the highest velocities. Downstream is observed between piers 1 and 2, that velocity increases with the consequent decrease of the intensities. This effect is more evident between piers 2 and 3. Between piers 3 and 4 are observed intensities greater than velocities, and it seems that the behavior described is not fulfilled; however, it must be remembered that the streamline followed by the sediments is the same flow line due to the curvature of the channel in this zone (Figure 3h).

This work showed that measuring flow discharge from bridges using acoustic Doppler equipment is a good practice and that they have an error of less than 1.5%. In addition, measuring with Doppler equipment allows the visualization of hydrodynamic fields. This helps to understand the interaction effects between the flow and the bridge piers and detect areas of erosion and deposition. Finally, one more contribution of the measurement with Doppler equipment is the visualization of the sediment suspend concentration areas. This is more significant in low velocities areas and decreases in higher velocities. For example, this knowledge can be applied in the location of intake drinking waterworks, where it is essential to choose the area with the lower sediment concentration.

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