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Real-Time Flow Measurement In The River Guadiana Estuary Using Acoustic Doppler Technology

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Abstract- **In the year 2004 a system was designed, installed and tested in the River Guadiana coastal plain estuary to provide with real-time net flow data to the Automatic Hydrological Information System, which is the control and monitoring tool of the River Guadiana Water Authority.**

I INTRODUCTION

The 'Confederación Hidrográfica del Guadiana' (CHG) is an autonomous organism belonging to the Spanish Environment Ministry, with providences over the water in Guadiana river, which runs for 60.256 km^2 (11.600 in Portugal and rest in Spain) [2].

The Hydrologic Information Automatic System (SAIH) is designed to provide real-time information about the hydrological and meteorological status of the water basins, to prevent and control floods and to ensure a reasonable use of hydraulic resources. Moreover SAIH includes phonic communications and wide area network in the whole space of the water basin [1].

The system, developed by Adasa Systems, relies on 86 gauging and control stations, 48 reservoirs, 13 channels, 154 meteorological stations and 12 level measurement stations, all of which are monitored in real-time from one main central station and 5 secondary stations.

The Guadiana River crosses the Spanish border into Portugal in Badajoz, and continues, leaving the Alqueva reservoir until return to be the natural border near the Chanza reservoir. Then it runs for 40 km until arrive to the Atlantic Ocean. It is easy to understand that it is a very important point for flow measurement, not only because of the estuary condition, but also due to both reservoirs' regulation.

The last control structure is located in Mértola (Portugal), so until this point of the river, it is under influence of tides. According to the Cameron and Pritchard's definition, adapted by Dyer (1997): 'An estuary is a semi-enclosed coastal body of water which has a free connection to the open sea, extending into the river as far as the limit of tidal influence, and within which sea water is measurably diluted with fresh water derived from land drainage' . The Guadiana River can be considered, until Mértola an estuary.

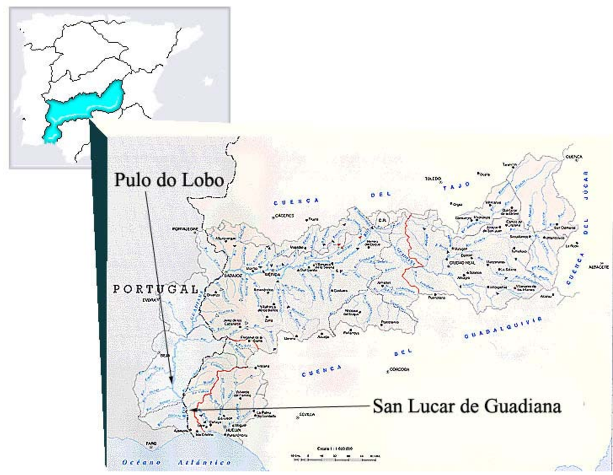

Fig 1. CHG water basin

The target in this work is threefold: instantaneous flow calculation on flood and normal conditions, net flow calculation and real-time information delivery to the SAIH central station.

II MEASUREMENT INSTALLATION

The measurement station is located in Sanlúcar del Guadiana (Huelva, Andalucia), 35 km away from the river outlet. In order to choose this location, the criteria were looking at:

- Accessibility
- Straight lengths: mainly looking upwards.
- Bed slope.
- Bathymetry: clean of obstacles on Doppler sensor sight.
- River velocity distribution: the area with maximum velocity was selected to install the sensors (Fig 2).

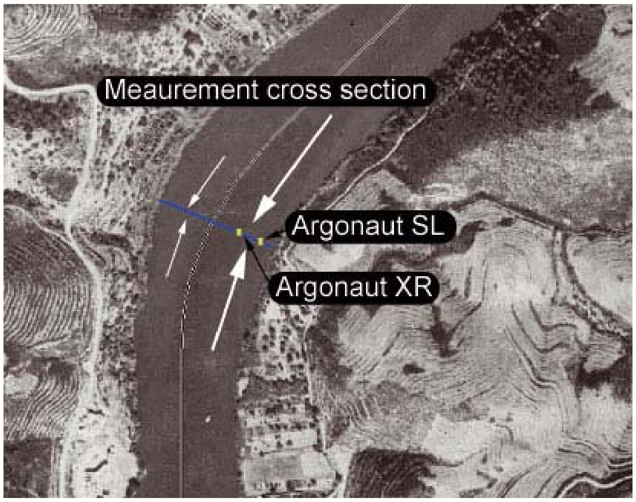

Fig 2. Aerial picture of point

The estuary can be classified topographically as coastal plain, and by salinity structures as well-mixed. The maximum and minimum flows measured are about ± 600 m^3/s, with a well-controlled continental flow by Alqueva and Chanza reservoirs. During the study there was not any flood situation, the continental flow was never bigger than 100 m^3/s.

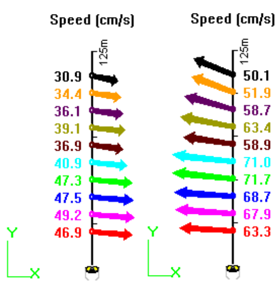

Fig 3. Velocity profiles measured by Side Looking sensor

Measuring equipment

The real-time system consists of 2 velocity sensors with an internal pressure sensor and one calculation unit with an internal atmospheric pressure sensor.

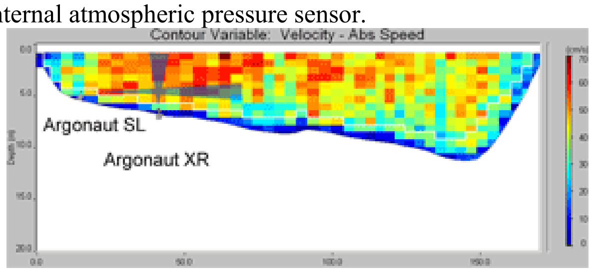

Fig 4. Measurement cross section scheme

Velocity measurement is done by Acoustic Doppler Profilers (ADP), one with horizontal beams (Argonaut Side Looking, Sontek –SL-) and one vertical (Argonaut eXtended Range, Sontek -XR-)[8].

The level calculation is made by relative pressure measuring, taking pressure data from the SL internal sensor compensated with the external pressure sensor.

Real-time calculation and its integration into the SAIH system is done by the Qualitas FLow calculation unit (QFL). Flow and level data are delivered using analog outputs to the SAIH remote station, connected to the central station using a TETRA radio net.

Sensors installation

ADP sensors were installed 12 m (SL) and 35 m (XR) away from the left edge (Fig 4). The sensors were anchored to the bed using concrete cubes, measuring 0.5 x 1 x 1 m, to which it were fixed steel AISI 316 structures (Fig 5).

Fig 5. Steel structures which fix the sensors to the concrete cubes (SL left and XR right).

The settlement of the cubes lasted 10 days. The internal XR compass indicates rotation not bigger than 3 degrees. Analysing velocity data from SL, the constant direction difference from 90 º indicates rotation of 5 º. Both direction rotations are corrected in the QFL.

III HYDRAULIC MODEL

Hydraulics in an estuary must consider horizontal and vertical velocity distribution, and the tidal component of flow.

Horizontal velocity distribution is made by SL (VSL), in a measuring range of 3-60 m (34 % of total), with cells until 115 m, of 10 m each. Vertical velocity distribution is measured by XR (VXR) measuring in 10 cells (i) of 0.6 m each (V_{XRi})

Mean velocity

The mean velocity calculation is done by two models working in parallel: velocity indexing with three factors and vertical proportion law.

Velocity indexing with 3 factors is based on the velocity indexing formula recommended by velocity-indexing method [6], improved with second sensor velocity data. This model introduces vertical measured velocity (V_{XR}), stage (h)-V_{XR} interaction and V_{XR}-V_{SL} interaction

$$V_m = V_{XR}(b_{vxr} + b_h.h + b_{vsl}.V_{SL}). \qquad (1)$$

Where b are the model coefficients.

The vertical proportion law is an adaptation of the power law. In natural streams with one horizontal beam solution this model describes vertical velocity distribution from the stage/sensor height ratio:

$$V_m = k.a.V_{SL}$$
$$k = \frac{6}{7}\left(\frac{h}{z}\right)\exp\left(\frac{1}{6}\right), \quad (2)$$

Where 'a' is a constant, which means that horizontal distribution will not change significantly (Fig 3).

In this case, when vertical distribution can be measured directly, we use the ratio between mean velocity (V_{XR}) and the velocity in the cell where both horizontal and vertical beams intersect.

$$V_m = (V_{XR}/V_{XRi}).a.V_{SL}. \quad (3)$$

Both models work in parallel, waiting for a validation under flood conditions (flow bigger than 600 m^3/s).

The flow calculation is made into the calculation unit. The mean velocity is calculated with the index velocity model (1). The stage is calculated using differencial pressure measurement. Finally the section is calculated in the calculation unit, using a 20 rows matirx for river geometry.

Net flow

The instantaneous flow calculated previously is composed by continental, tidal and one residue, with hysteresis, wind and non-linear components

$$Q_{inst} = Q_{cont} + Q_{tidal} + R \quad (4)$$

Q_{tidal} is composed of several harmonics movements with the frequency of the generators of total forcement of tides, which are associated to relative movement of the World-Sun-Moon system[5]

$$\eta(t) = \sum_i a_i \cos(\omega_i t + \phi_i) + R(t) \quad (5)$$

If Q_{inst} is integrated during one of the tidal harmonic periods and then is divided by this period, the result will be the mean net flow, without the component of such harmonic. Repeating this mean integral for each harmonic, the net flow will approach Q_{cont}.

IV MODEL ADJUSTMENT

The model adjustment was made with data from 18 gauging measurement and data from the SL and XR internal logger (velocity and pressure) and from the QFL internal logger.

Mean velocity

To calculate parameters in (4), the first step was to study which cell in XR is intersecting the SL beam. Studying the rms of difference between velocities in intersecant cells, it was obtained the lower values between cell 5 of SL and cell 1 of XR (0.5 – 1.1 m). Then a coefficient is calculated with the mean value obtaining V_{sl} from SL logger and V_m from 12 gauging in three different conditions. The lineal regression using the model (3) resulted $r^2 = 0.98$,

$$V_m = 0.758.(V_{XR}/V_{XRi}).V_{SL}. \quad (6)$$

Coefficients b in model (1) were calculated using the index-velocity method, for 2 factors velocity indexing (sensor velocity and sensor's velocity-stage interaction), and introducing the third factor (interaction V_{SL}-V_{XR}). The three factors resulted significant, improving the model up to r^2 = 0.99,

$$V_m = V_{XR}(0.508 + 0.023h - 0.114V_{SL}). \quad (7)$$

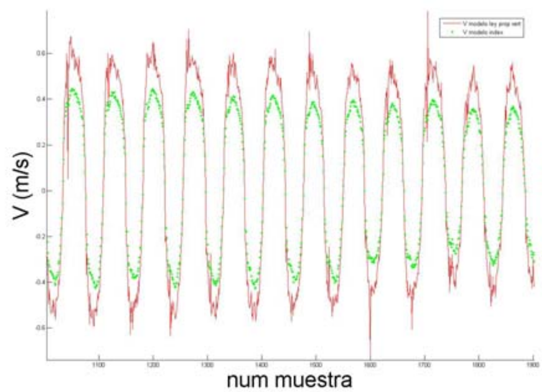

Fig 6. Mean velocity calculated by vertical proportion law (red, solid) and index velocity (green, dotted)

The plot in Fig 6 indicates that vertical proportion law is not adequate in normal conditions, where tidal forces makes V_{XR1} tend to 0 harmonically. Instead, in this conditions index velocity (1) is very stable.

It is necessary to test both models in flood conditions to discard one of them, or to decide to run the combination of index velocity in normal conditions and vertical proportion in floods.

Net flow

The harmonics which can be considered in the estuary are multiple: semidiurnal, diurnal or monthly, relative to the moon, sun or both. Each one will have a different period.

The principal harmonics observed in this case are moon semidiurnal (ms = 89400 sec) and moon diurnal (md = 44700 sec). Then to calculate Q_{cont} from (5) it must be integrated and divided by periods

$$Q_{\text{int}}(m^3/s) = \frac{\int_{t-sl}^{t} \frac{\int_{t-dl}^{t} Q_{inst}(m^3/s)}{dl(seg)}}{sl(seg)} \quad (8)$$

The smoothing, observed in Fig 7, is obtained with each integral's step of (8)

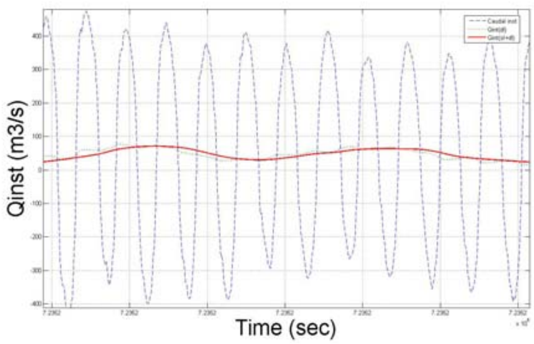

Fig 7. Instantaneous flow (dash), integral over ms (dot) and mean integral over ms and md (continuous).

V NET FLOW VALIDATION

The double integral described in (8) was used to calculate mean net flow of the last 24.83 hours in Sanlúcar del Guadiana. The result was accumulated during a 20-day period.

The same was done with Pulo do Lobo flow data, which is a station located 51 km upwards from Sanlúcar de Guadiana. Between both stations there were no significant contributions.

Instantaneous flow data is not comparable, due to the long distance of the natural stream between stations, so the validation was done only with totalized flow Fig 8.

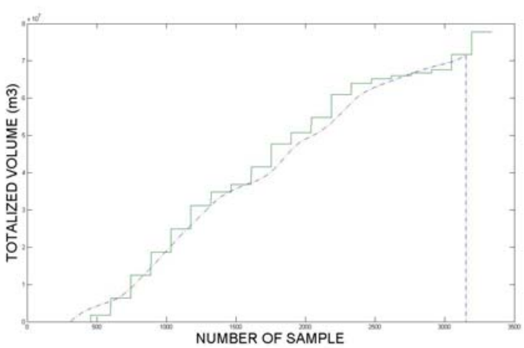

Fig 8. Totalized flow in Pulo do Lobo (green, solid) and SanLúcar del Guadiana (blue, dash-dot) between 21/11/04 al 11/12/04.

The volumen difference between totalized in Pulo do Lobo and the volumen totalized in Sanlúcar del Guadiana during the 20-day test was lower than 3 %.

VI CONCLUSIONS

Real-time flow measurement in estuaries can provide two types of data: instantaneous flow and net flow. The net flow will be the mean integral of the harmonics observed in the flow data.

The mean velocity is well described with an velocity-indexing method, introducing velocity and stage. The velocity should be measured in vertical and horizontal profiles.

In coastal plain and well-mixed estuaries, as the Guadiana estuary in Sanlúcar del Guadiana the net flow (mean net flow of the last 24.83 hours) can be measured with an accuracy better than 5%.

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