# CNR Kaplan turbines: assessment of flow rate measurements by acoustic scintillation using Winter-Kennedy and ADCP measurements

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## Introduction

The Compagnie Nationale du Rhône (CNR) has 19 hydropower plants of which 18 are low head plants. In the framework of improving knowledge of the flow rates passing through CNR's hydropower turbines, experimental and flow rate measurement qualification tests were performed in 2009 by using acoustic scintillation flow measurement (ASFM: Acoustic Scintillation Flow Meter) on a site equipped with Kaplan turbines. The measurements were carried out at the Châteauneuf-du-Rhône hydropower plant, about 150 kilometres downstream of Lyon. Launching the operation required adapting to operating constraints and the fabrication of three steel frames to support the ASFM sensors, adaptable to several CNR hydropower plants equipped with Kaplan turbines. Each CNR plant equipped with Kaplan turbines has three intake bays per turbine.

The ASFM measures the flow velocity by analysing the turbulence of the water. Initially, thirty measurement acoustic paths were installed in each of the three intake bays upstream of turbine unit 5 and provided data on the velocity field. This analysis then permitted reducing the number of acoustic paths per intake bay to ten, determining the optimal distribution and performing measurements simultaneously in the three intake bays to obtain the absolute flow rate of turbine unit 5.

In parallel, the absolute flow rate of turbine unit 5 was also determined for different flow rates, by portable ultrasound measurement using Acoustic Doppler Current Profiler (ADCP) sensors immediately downstream of the plant. It was not possible to operate turbine unit 5 alone since the minimal flow rate of the Rhône is higher than the maximum admissible value for a single unit. It was therefore necessary to adapt the "river ADCP" procedure usually used with the ADCP. Initially, the total flow rate downstream of the plant was measured with turbine unit 5 stopped. Then the total flow rate of the plant was measured with unit 5 in operation. The difference in the two modes permitted obtaining the variations attributable to unit 5 alone. This method required operating at different flow rates in unit 5 while maintaining constant flow rates in the other five units.

The Winter-Kennedy (WK) method was used to determine the relative flow rates on the basis of differential pressure measurements. The principle of this method relies on the correlation between the flow rate passing through the turbine and the difference in pressure between the concave and convex surfaces of the turbine scroll (or semi-scroll) case. Determining the absolute flow rate depends to a great extent on the value chosen for the turbine's optimal output.

Following these different tests, it was seen that the flow rate values stemming from the three methods, ASFM, WK and ADCP converged within a range of 3%. This paper presents the analysis of the flow rates resulting from these three measurement methods, independently of each other.

# 1. Acoustic scintillation method

## 1.1 Presentation

The ASFM uses a technique called acoustic scintillation drift to measure the flow velocity perpendicular to a number of acoustic paths established across the intake of the turbine. Short pulses of high-frequency sound are sent from transmitting arrays on one side to receiving arrays on the other side. Fluctuation in the amplitude of those acoustic pulses result from the turbulence in the water carried along by the current. The ASFM measures those fluctuations and from them computes the lateral average (i.e. along the acoustic path) of the velocity perpendicular to each path. The signal amplitude at the receivers varies randomly as the turbulence along the propagation paths changes with time and flow. If the two paths are sufficiently close ($\Delta x$), the turbulence remains embedded in the flow, and the pattern of these amplitude variations at the downstream receiver will be nearly identical to that at the upstream receiver, except for a time delay $\Delta t$. This time delay corresponds to the position of the peak in the cross-correlation function calculated for upstream and downstream signals. The mean velocity perpendicular to the acoustic paths is then $V=\Delta x/\Delta t$. The ASFM computes the discharge through each bay of the intake by integrating the horizontal component of the velocity over the cross-sectional area of the intake. The discharges through each bay are then summed to compute the total discharge.

## 1.2 Location

The ASFM sensors were installed in the stop-log slot, as indicated in *Fig. 1*. Note that it is really important to be far enough downstream of the five trash rack elements, generating isotropic turbulence in the measurement plane.

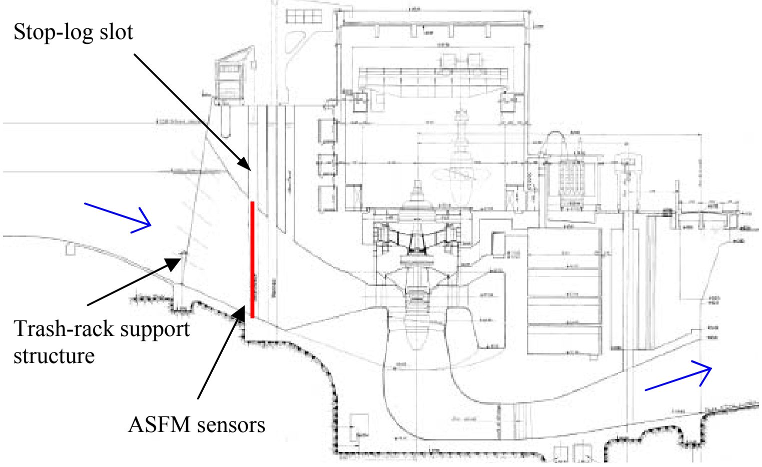

*Fig. 1. Vertical cross-section of Châteauneuf-du-Rhône intake and location of the ASFM sensor plane in G5 intake*

Diagnostic measurements were needed to resolve the water velocity variations at the instrument measurement plane. Since the equipment rental only included thirty ASFM transducer pairs, ten transducer positions needed to be selected for each of the three frames – one set for each intake bay. Velocity measurements were first conducted in Bay 1 with the 30-path frame for three flow settings (130, 200 and 290 m$^3$/s) of the unit. Similar measurements were then conducted in Bay 2 and 3 of G5. Based on this data, optimum positions for the ten paths on each of the three frames were selected.

The three frames used at Châteauneuf-du-Rhône were designed such that they could be used at four individual CNR hydroelectric plants: Bourg Les Valence, Beauchastel, Logis-Neuf and Châteauneuf-du-Rhône. The bottom cross member is designed such that it rests on the sill and no water can pass under it. The side faces are designed to sit flush with the intake walls once the frame is lowered into place. As part of the work, divers verified the position of the frames with respect to the wall.

## 1.3 Measurement accuracy

The replicate runs made at each condition allowed an estimate of the random error in the ASFM flow measurements to be calculated. The average fractional standard deviation of the discharge at each test point is 1.1% and the maximum is 3.3% occurring at a flow of only 25.5 m$^3$/s.

For each flow rate measured, the global uncertainty is the combination of systematic uncertainties *S* and random uncertainties *R*.

$$E = \sqrt{S^2 + R^2} \tag{1}$$

The systematic uncertainty is estimated at +/- 1% by the constructor. The random uncertainty ranges from 0.75% to 2.3% for flow rates over 90 $m^3/s$. The global uncertainty is therefore between 1.3% and 2.5%.

# 2. ADCP method

## 2.1 Presentation

The ADCP sensor uses the Doppler effect to measure flow rates. It is usually used to gauge the flow rates in rivers. The sensor is installed on a boat and immerged several centimetres below the surface. An ultrasound pulse is emitted from the sensor in the water toward the river bed. The suspended particles in the water reflect the sound wave back to the ADCP sensor which then analyses the shift in frequency between the wave emitted and that received to determine the speed of each cell in the column of water under the sensor. The flow rate of the river is computed by integrating the velocities travelling across the river from one bank to the other with the sensor immerged. Each crossing forms a transect that provides the elementary flow rate. The mean of several transects is used to provide a reliable estimation of the flow rate.

## 2.2 Specific procedure set up at Châteauneuf-du-Rhône

To determine the flow rate passing through turbine unit 5, it would have been convenient to gauge the flow rate downstream of the Châteauneuf-du-Rhône hydropower plant when unit 5 was operating alone. However, it was not possible to perform the operation in this way since the minimum flow rate of the Rhone at this section is about 400 $m^3/s$, in excess of the maximum admissible flow rate for a turbine unit. The principle for estimating the flow rate discharged by turbine unit 5 (denoted $Q_{G5}$) based on the measurements performed with the ADCP was to work by varying the flow rates passing through G5 only, with the other turbine units operating at constant flow. Hence the following procedure was established, consisting of:

- maintaining a constant basic flow rate Q0 with the other turbine units (excluding G5), lasting throughout the operation. It was measured when G5 was at standstill;
- stepping up the flow rates of G5. For each step, the variations attributable to G5 ($Q_{G5}$) were then calculated by differences:

  $$Q_{G5} = \sum_{n=1}^{6} Q_{Gn} - \sum_{n=1}^{6} Q0_{Gn} \text{ with } Q0_{G5} = 0 \text{ (with turbine unit 5 initially at standstill) ;} \tag{2}$$
- maintaining a flow rate setting for at least two hours to ensure at least 30 minutes of gauging without the passage of boats is available, while at the same time maintaining navigation (it should be noted that each downstream lockage generates an additional flow when emptying the lock chamber);
- maintaining the impeller/valve in fixed positions by switching to manual mode and bridling the sensors upstream and downstream of the plant to fix the head seen by the operating computer;
- inhibiting the primary frequency setting;
- integrating the variation of the head to compute the change of basic flow rate Q0 for the different settings (even if the impeller/valve positions of the turbine units can be maintained artificially, any variation of the head leads to modifying the flow rates of the turbine units);
- increasing the number of ADCP sensors to reduce random errors.

The experiment showed that carrying out several measurements simultaneously with different ADCPs makes it possible to converge to the true flow rate value. To achieve this, ten ADCPs were used simultaneously downstream of the hydropower plant.

Afterwards, an analysis was performed on all the measurements to observe the influence of the number of ADCP sensors used on the value of the setting chosen. It was seen that using ten ADCPs greatly increased measurement precision. The standard deviation for all the ADCPs was in the region of:

- 1% provided that seven to ten ADCP sensors were used;
- 2% provided five to seven ADCP sensors were used;
- up to 7% with a single ADCP sensor, depending on the ADCP sensor chosen.

## 2.3 ADCP measurements

The charts of *Fig. 2* illustrate the three flow rate settings measured by ADCP on 29 October and 3 November 2009, in conformity with the procedure described in the previous paragraph.

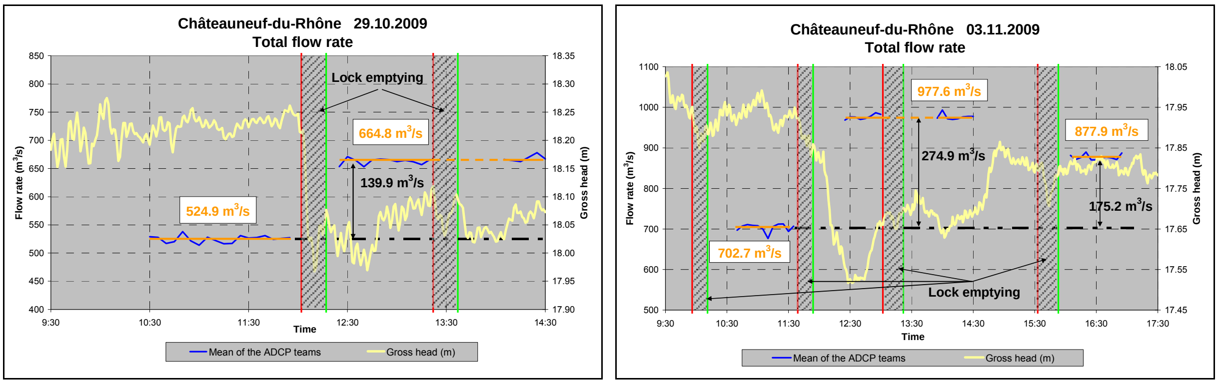

*Fig. 2. Flow rate settings measured by ADCP on 29/10/2009 and 03/11/2009*

These charts show the mean ADCP flow rate measurements and the head at the hydropower plant.

*Table 1* gives the values of the flow rate settings determined from ADCP measurements.

| | Settings | | |
|---|---|---|---|
| | -1- | -2- | -3- |
| **Mean flow rate (m$^3$/s)** | **139.9 m$^3$/s** | **274.9 m$^3$/s** | **175.2 m$^3$/s** |
| Standard deviation (m$^3$/s) | 5.6 m$^3$/s | 5.8 m$^3$/s | 6.4 m$^3$/s |
| Standard deviation (%) | 4.00% | 2.10% | 3.70% |

*Table 1. Flow rate settings measured by ADCP on29/10/2009 and 03/11/2009*

## 2.4 Taking into account the gross head

The variation of flow rate observed with the ADCP downstream of the Châteauneuf-du-Rhône hydropower plant between the initial setting (flow rate Q0: turbine unit 5 at standstill and head H0) and each setting (flow rate Q: unit 5 in operation with flow rate $Q_{G5}$ and head H), is influenced by the flow rate of turbine unit 5 and also by the variation of the head according to:

$$Q - Q0 = Q_{G5} + \left( \sum_{n=1}^{4} Q0_{Gn} + Q0_{G6} \right) \times \left( \sqrt{\frac{H}{H_0}} - 1 \right) \tag{3}$$

It should be noted that the previous relation is valid only if the variation of the head remains lower than 2%, which was the case on 29 October and 3 November 2009.

The real head observed was monitored and recorded by installing level sensors/recorders at measurement points upstream and downstream of the hydropower plant usually used for operating the latter. They were both located on the right bank about 100 metres on either side of the plant. The up and downstream sensors recorded variations of water heights in relation to a single reference height. The head resulting from the difference between the upstream and downstream heights can be considered as low +/-5 cm.

*Table 2* gives the flow rates settings attributable to turbine unit 5 by taking into account the variation of the gross head.

The discharges of turbine unit 5 determined by the ADCP measurement procedure corrected for the variation of head can be considered as correct to within 3% without it being possible to fix the true value. A finer metrological analysis of the ADCP procedure did not result in reducing this uncertainty due to the absence of values linked to a benchmark. A similar test is programmed downstream of the Génissiat power plant (on the Rhône, about 150 km upstream from Lyon) in October 2010 to compare the ADCP values with the reference values resulting from the instrumentation of penstocks by known sensors ("OWICS" method, cf. annex J of the standard IEC 60041).

|  | Setting 1 |  | Setting 2 |  | Setting 3 |  |
|---|---|---|---|---|---|---|
|  | initial | final | initial | final | initial | final |
| Elevation upstream of plant (m NGF ortho) | 76.91 | 76.85 | 76.67 | 76.57 | 76.67 | 76.63 |
| Elevation downstream of plant (m NGF ortho) | 58.7 | 58.78 | 58.74 | 58.88 | 58.74 | 58.8 |
| Head (m) | 18.22 | 18.05 | 17.94 | 17.62 | 17.94 | 17.81 |
| Variation of head (%) | -0.90% |  | -1.80% |  | -0.70% |  |
| Variation of flow rate attributable to variation of head | -0.50% |  | -0.90% |  | -0.40% |  |
|  | -2.4 $m^3/s$ |  | -6.3 $m^3/s$ |  | -2.5 $m^3/s$ |  |
| Flow rate settings measured with ADCP ($m^3/s$) | 139.9 $m^3/s$ |  | 274.9 $m^3/s$ |  | 175.2 $m^3/s$ |  |
| **Flow rate setting attributable to G5 ($m^3/s$)** | **142.3 $m^3/s$** |  | **281.2 $m^3/s$** |  | **177.7 $m^3/s$** |  |
| Increase due to variation of head (%) | 1.7% of Q(G5) |  | 2.2% of Q(G5) |  | 1.4% of Q(G5) |  |

*Table 2. Taking into account the variation of gross head*

## 3. Winter-Kennedy method

### 3.1 Presentation of the method and localisation of pressure taps

The principle of the method is based on the correlation between the flow rate passing through the turbine and the difference in pressure between the concave and convex surfaces of the turbine scroll case. This method is described in detail in international standard IEC 60041/AC1.

Three pressure taps were used for turbine unit 5: two internal sensors (2’ and 3) and an external sensor (1).

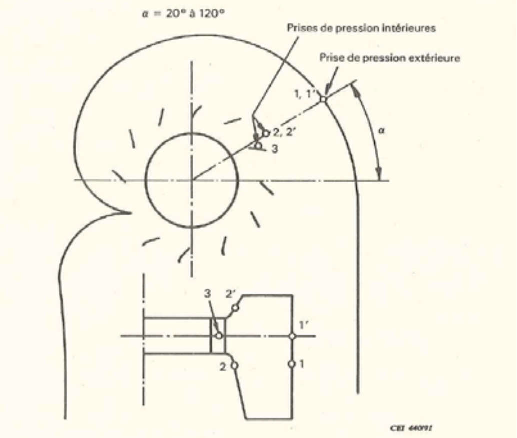

*Fig. 3. Localisation of WK pressure taps in the scroll case*

The method assumes that the flow rate passing through the turbine is generally expressed with sufficient precision by relation $Q = K\Delta H^n$, where $\Delta H$ is the differential pressure (concave-convex) and *n* is an exponent theoretically equal to 0.5. It should be noted that the standard indicates that this coefficient can vary from 0.48 to 0.52 under unfavourable conditions, such as low speed or in the case of semi-scrolls (cf standard IEC 60041/AC1).

In practice, it is first necessary to calculate coefficient *K*. To do this, it is usual to start from the optimal output of the turbine unit, i.e. a point of maximum output. The output value is then determined on the output curve provided by the most recent tests or, failing these, it is taken as being equal to the value provided by the constructor. The fact of setting an output for calculating *K* implies that this method only supplies a relative flow rate and not an absolute one, as in the case for the ASFM and ADCP methods.

Secondly, measuring the power and head allows calculating the flow rate and thus deducing coefficient *K*. This coefficient is then used for all the tests.

- step 1: adjustment to the turbine optimum;

- step 2: arbitrary choice of output: η (for turbine unit 5, an output of 90% is taken into account as the optimum of the turbine unit);
- step 3: measurement of the active power ($P_a$) and the net head ($H_n$);
- step 4: flow rate calculation.

With:
$P_n$: the theoretical power of the turbine: $P_n = \rho.g.Q.H_n$ (4)
$P_a$: active power
$\eta = P_a / P_n$ (5)
(4) and (5) → $Q = \frac{P_a}{\eta.\rho.g.H_n}$ (6)

Since turbine unit 5 has three pressure taps, two *K* coefficients are calculated and at each test it is possible to determine two flow rate values ($Q_1$ and $Q_2$), corresponding to two pairs of differential pressure measurements.

### 3.2 Results

The Winter-Kennedy measurements were performed in parallel with the ADCP measurements of the flow rate settings on 29 October and 3 November 2009 by way of comparison. WK measurements were also performed on 2 November 2009 on the existing linking cam (ten points were measured). It should be noted that values $Q_1$ and $Q_2$ are very close. The homogeneity criterion of the flow rate values generally taken into account in the Winter-Kennedy method, i.e. $0.98 < \frac{Q_1}{Q_2} < 1.02$, were respected for all the tests performed. The turbine flow rate values are calculated by obtaining the mean of the values ($\frac{Q_1 + Q_2}{2}$).

On the basis of the mean differential pressures values, it was possible to determine the values of the flow rates through turbine unit 5 during the different settings.

Measurement fluctuations: fluctuations of the differential pressures measured during each setting $\frac{\sigma\ (standard\ deviation)}{m\ (mean\ value)}$ are lower than 3%. This value is a good indicator of the fluctuation of flow rates passing through turbine unit 5 during each setting. By considering relation $Q = K\Delta H^{0.5}$, the fluctuation of flow rates through turbine unit 5 for each setting is very low, about 1.5%, which proves the stability of the flow rate passing through turbine unit 5. The fluctuations of heads during the different settings are quite low, about 1% (value calculated by considering 95% of the head values), and are certainly the main reason for the fluctuations observed in the flow rate of turbine unit 5.

Measurement accuracy: regarding measurement precision, it is commonly accepted that the WK method provides relative output (and thus flow rate) with a precision of 0.5%. In addition, checks were made that the blade positions and gate positions were fixed during the different settings. However, the measurements of blade positions were performed with position sensors with a resolution of 0.5 mm, which corresponds to a flow rate variation of 0.5 $m^3/s$ for each Kaplan turbine of the Châteauneuf-du-Rhône hydropower plant. Thus the method used cannot detect flow rate variations of 2.5 $m^3/s$ at most for the five turbine units other than turbine unit 5. This observation shows that the possible instability of the turbines whose operation is assumed to be constant has negligible influence on the estimation of the flow rate of turbine unit 5 (less than 1% of the flow rate of turbine unit 5).

Given the elements described above, the uncertainty expected of the relative WK flow rate measurements of turbine unit 5 during the different settings is in the region of 1.5%.

## 4. Comparison of flow rates resulting from ASFM, the ADCP procedure and the WK method

*Table 3* gives the flow rates passing through turbine unit 5 of Châteauneuf-du-Rhône measured by the three methods for the three settings of flow rates performed on 29 October and 3 November 2009.

It can be seen that:

- the values of the ASFM flow rates are very close to the absolute flow rate values measured by ADCP, with differences of less than 3%;
- the ASFM flow rate values are consistent (relatively constant deviation) with the relative flow rate values provided by the Winter-Kennedy (WK) method;
- the WK method leads to flow rates up to 4% lower than those determined by ADCP and ASFM. This can be explained either by the assumption of an output lower than the 90% optimal flow rate of the turbine, or by the uncertainty on these three methods.

| Date | ADCP | WK | ASFM | Difference of ASFM vs ADCP | Difference of ASFM vs WK | Difference of WK vs ADCP |
|---|---|---|---|---|---|---|
| | Q ($m^3$/s) | Q $\eta$=90%, with inclusion of net head ($m^3$/s) | Q ($m^3$/s) | | | |
| 29-Oct-09 | 142.3 | 142.7 | 146.7 | 3.1% | 2.9% | 0.3% |
| 03-Nov-09 | 177.7 | 170.1 | 176.4 | -0.7% | 3.7% | -4.3% |
| 03-Nov-09 | 281.2 | 273.4 | 283.6 | 0.9% | 3.7% | -2.8% |

*Table 3. Comparison of flow rates determined by ASFM, the ADCP procedure and the WK method*

The flow rates provided by the three methods are very close. In a general way, the choice of method to be used will be made as a function of the parameters to be measured. *Table 4* gives the advantages and disadvantages of the three methods used.

| | Advantages | Disadvantages |
|---|---|---|
| ASFM | - knowledge of the absolute flow rate<br>- installation and measurements only affect the turbine to be measured<br>- fairly fast measurements<br>- possibility of carrying out measurements over long periods (determination of $Q_{head}$ laws for example) | - cumbersome and demanding installation of sensors: installation fixed for several weeks to several months (problem of cost and immobilising equipment)<br>- long preparation (frame, seeking the optimal position of arrays) |
| ADCP | - knowledge of the absolute flow rate<br>- no specific instrumentation on the turbine and more generally inside the plant<br>-mobile outfit adaptable for any plant | - 4h of operation on site to measure one flow rate<br>- constraints imposed on the other turbines of the plant |
| WK | - very fast measurements<br>- little installation to be provided if pressure taps exist in the civil engineering structure | - absolute flow rate unknown<br>- need to have pressure taps |

*Table 4. Advantages and disadvantages of the different methods*

## 5. Conclusion and perspectives

The ADCP measurements on site on 29 October and 3 November 2009 show that the discharge of turbine unit 5 can be determined while the other turbine units are in operation, by working on the difference between flow rates. It is necessary to incorporate head variations to offset the fact that the flow rate in the other turbines changes slightly between the different settings. This correction stemming from the head measurements is in the region of 2% of the gross ADCP flow rate.

The discharges from turbine unit 5 determined by the ADCP measurement corrected for head variations can be considered as correct to within 3% without it being possible to set a true value. A finer metrological analysis of the

ADCP procedure did not permit reducing this uncertainty due to a lack of benchmark values. A similar test is programmed for Génissiat in October 2010 to compare the ADCP values with the reference values provided by conduits fitted with known sensors.

It appears that the ASFM and WK flow rate values are relatively homogenous, to within a single multiplication factor, which could be due to a lower output of turbine unit 5 and/or an error in the accuracy of the ASFM and/or WK measurements.

The flow rates measured by the ADCP and the Winter-Kennedy method performed on turbine unit 5 of the Châteauneuf-du-Rhône hydropower plant validated the flow rates measured by ASFM.

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## The Authors

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**Pierre Roumieu** graduated in Hydraulics from the Ecole Nationale Supérieure d’Hydraulique et Mécanique de Grenoble. He has worked for ten years in CNR’s hydraulics and materials testing laboratory. During this period, he has designed a large number of hydraulic structures in river and torrential environments (with sediment transport) as well as in the field of pressure hydraulics. Over the last six years he has carried out detailed studies, diagnostics and designs for lock filling systems and has been in charge of the laboratory’s physical modelling activity for five years. He is currently heading a study on a physical model of the future wide gauge lock at Cremona (Italy). Before 1998 he was involved in numerous hydraulic projects (particularly the Rhine-Rhône wide gauge waterway project) as a mathematical modelling specialist.

**Christophe Montbroussous** graduated as an Electrical Engineer from INP Toulouse. He joined the Compagnie Nationale du Rhône in 1996 as a business development engineer for different upgrading projects performed on installations on the Rhone. From 2001 to 2006, while setting up the CGPR (Rhone Production Management Centre), he was in charge of organising and developing the management and optimisation of non-availabilities and constraints of hydropower turbines and managing the centre's operational activity. From 2007 he was also in charge of CNR' relations with its client Réseau de Transport d’Electricité and joined the industrial policy, operations and performance department in which he is responsible for performance. In particular, in 2009 he managed the team that performed the experiments involving the qualification of turbine flow rate measurements using acoustic scintillation on a Kaplan turbine.

**Jan Buermans** graduated in Mechanical Engineering from Queens University, Kingston Ontario, Canada. He joined ASL AQFlow in 2002 as Sales Manager and Project Manager. He also has responsibilities for providing assistance with the design of the mounting frames and hardware for the ASFM. He is a licensed engineer in the Province of British Columbia, Canada. In particular, in 2009 Jan managed the ASL team that performed the ASFM measurements discussed in this paper.