Hydrometry: measuring the flow rate of a river, why and how?

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Predicting and managing river flows is a necessity for flood control, water supply, agriculture and energy production. However, knowing how to measure these flows is a prerequisite. This constitutes hydrometry, a science distinct and complementary to hydrology (science of water in its natural environment) and hydraulics (physics of flows). About one-third of the rain that falls on the continents returns to the sea and oceans (the other two-thirds evaporating directly or being consumed by plants). On a global scale, nearly 36,000 km^3 of water flows through rivers each year. But these quantities can be very unevenly distributed, both from one continent to another, and - for the same river - from one year to another or within the same year. This irregularity can only be approached by permanently measuring the flows of these rivers. However, the continuous measurement of the flow of a watercourse cannot be obtained directly, but is the result of an experimental process combining several field observations..

1. Measuring river flow rates, an old but difficult issue

Figure 1. L'Ouvèze at Vaison la Romaine; the flow of this river of Provence has been able to increase from 0.1 m^3/s - left photo, summer 1990- to nearly 1200 m^3/s- right photo, September 22, 1992- this for an average annual flow close to 6 m^3/s. [© EDF DTG]

Hydrometry, a science distinct and complementary to hydrology (science of water in its natural environment) and hydraulics (physics of flows), is the discipline that seeks to **measure river flows**. The flow rate -volume of water crossing a section of a stream for one unit of time- is expressed in cubic metres per second (m^3/s).

Each watercourse follows a **particular regime**, determined by the **rhythm of precipitation** and its hydrological "terroir". For the world's most populated river, the Amazon, the variation in flow between two extreme months of the same month is only one to two. And from one year to the next, its average annual flow at its mouth varies only 10 to 15% around its 206,000 m^3/s value. The **Amazon is an extremely regular river**.

On the other hand, an African river like the Chari has an average flow of 1197 m^3/s at its outlet in Lake Chad. Within the same year, the variation in flow between two extreme months is a factor of 20 (150 to 3000 m^3/s). And from one year to the next, the average annual flow can vary by a factor of two: 739 m^3/s in 1942, 1720 m^3/s in 1956. **The Chari therefore has a much more contrasting regime.**

But how are these flows measured? Since ancient times, mankind has been interested in it, at the *very least*, when it became dependent on agriculture. But it is a much more difficult problem than its familiarity would suggest. What made James Jeans (British physicist, 1877-1946) write: "The total radiation emitted by the Sun in the unit of time, transformed into mass, is something like 10,000 times that of the water flowing in the Thames under the London Bridge; and incidentally, if the factor 10,000 is gross, it is not because we do not know the exact mass of the solar radiation, but because we are not able to measure the average flow of the Thames. »

2. Why are river flow rates being measured nowadays?

The measurement of river flows serves several purposes:

operational management of hydraulic structures (hydroelectric facilities, irrigation systems, flood control tanks or low water level support systems, etc.);

the **dimensioning of** these structures, through knowledge of the characteristics of these watercourses;

regulatory control, for verification of flow release obligations downstream of structures (minimum flow to ensure fish survival, maintenance of other uses; non-aggravation of floods), declaration of disaster status (droughts...);

protection of property and persons, through flood warning;

of **heritage**, by the constitution of series of long-term observations, essential to know the evolution of river regimes, to raise awareness of natural risks, to assign a probability to extreme events (floods, low water levels).

Figure 2. Flow measurement station of the Isère in Grenoble on the university campus of Gières Saint-Martin d'Hères. [© LTHE (Laboratoire d'Etude des Transferts en Hydrologie et Environnement, now Institut des Géosciences de l'Environnement, IGE, Grenoble)]

The interest of these measures is now **reinforced** by the current challenges of **global warming**, new demands for **sharing water** between different uses (recreational, energy, irrigation, drinking water), the restoration or **preservation of natural environments** and their biodiversity, the **social demand for** knowledge, the **increased vulnerability of** society.

It should be noted that there are currently about **3500** hydrometric stations in metropolitan France, mainly managed by the Ministry of the Environment and by operators of hydroelectric or irrigation works. More than **80%** are teletransmitted in real time. This density (0.63/ 100 km^2) is in the **average of Western Europe**, about the same as that of the United Kingdom, higher than Spain, but lower than Switzerland or Germany.

3. How is the flow of rivers measured?

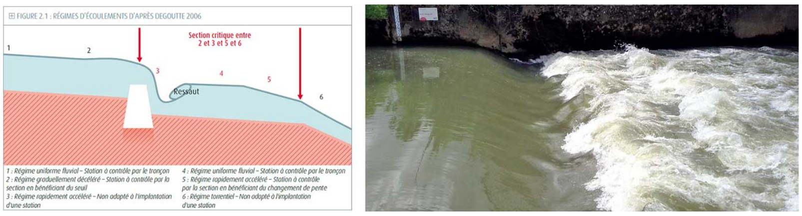

Figure 3. hydraulic control in the river; on the left, the principle diagram; on the right, an example in the river. Note the formation of a torrential flow regime as soon as the threshold is crossed, followed by a hydraulic jump producing eddies and a great loss of energy. [© EDF DTG]

Direct flow measurement is a complex operation that can only be performed occasionally. Except in very specific cases, direct and continuous monitoring of the flow cannot be carried out. It is the **water level** that is measured continuously, after having previously connected it to the flow rate by a **calibration curve**. This is why hydrometry is a **4-step** process:

the continuous measurement of **heights** upstream of a **hydraulic control** (see Figure 3), or at another location where a unique height-flow relationship can be established,

the realization of periodic **gauges** to build this relationship **(calibration curve**), allowing to convert the heights into flows,

the **layout of** this calibration curve and the **detection of its evolutions**,

then, after conversion of heights into flow, **critical** analysis of **spatial and temporal fluctuations**, then their archiving.

3.1. Continuously measure heights

For a long time, **height measurements** consisted of visual readings taken daily (or at a shorter frequency) on graduated scales (Figure 4). Over time, the process has become automated by the installation - in addition to these reference scales - of sensors to monitor height variations at a time step adapted to **flow** fluctuations (very reactive in the case of a small torrential basin; much smoother in a large plain river basin). Several generations of sensors now coexist on the networks: float, pneumatic, piezoresistive, ultra-submerged sound, differential conductivity measurement, etc....

Figure 4. Scale on Niger in Mopti. [© LTHE, now IGE]

All these devices are placed **in or in contact with water**; the **radar** (Figure 5) - which appeared at the beginning of the 2000s - offers the advantage of being out of the water (a guarantee of **better durability**, as it is **not subject to the aggressions of** water, sediments & bodies floating in rivers) and insensitive to **temperature (a** characteristic that is lacking with emerging ultra sounds). However, the need to move the radar away from the shoreline (edge effects) and the wave reception task conditioned by the waveguide may nevertheless penalize the representativeness of the measurement in relation to the reference scale.

Figure 5. Level measurement by emerged radar. [© EDF DTG]

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3.2. Calibrate the calibration curve: the gauges

Periodic gauging is carried out on the entire **range of flows** that the river can reach (in drought, medium water, and floods), mainly by exploring the velocity field or diluting a tracer.

The **gauging by exploring the velocity field** (Figures 6 and 7) of the flow has long been limited to surface velocities (by means of **"floats**", sticks weighted according to the current). More complete maps of **the velocity field** are now available using speed sensors: **mechanical reels** (Figure 6) - a propeller rotating in proportion to the local velocity of the current - **electromagnetic** - the displacement of water producing an induced voltage proportional to the local velocity of the current (Faraday Principle).

Figure 6. Hydrometric reel implemented at Grenoble Campus sur l'Isère station. [© LTHE, now IGE]

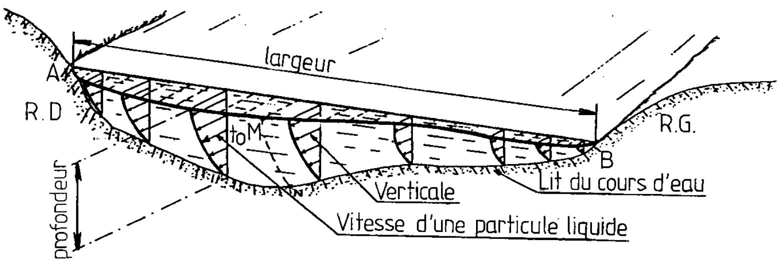

Figure 7. Principle of gauging by exploring the speed field. The speed map is plotted by 30 to 40 seconds of stationing at several depths and on several verticals.

Since the early 1990s, **ADCP profilers** (Acoustic Doppler Current Profiler: a device from oceanography, based on the Doppler effect) have been a **real technological leap forward** in hydrometry (Figure 8). They **significantly** reduce **on-site measurement time**, especially on large rivers, and are now suitable for small rivers (but a minimum depth of 50 cm is required).

Figure 8. The ADCP velocity measurement is based on the pulsed Doppler principle: emission of ultrasonic pulses into the water and analysis of the frequency offset of the backscattered echo of the suspended particles. The device generally has 3 or 4 transducers emitting divergent acoustic beams around the vertical, which allows the vertical profile of velocities to be measured in three dimensions. [© EDF DTG]

Figure 9. Left: Rhodamine injection device. Right: Rhodamine enters the stream. The tracer (harmless to fauna and flora) does not colour the water. Its dilution is then analysed by a fluorimeter (measuring the attenuation of its fluorescence), still today in the laboratory; tomorrow can be directly in the field [© EDF DTG]

Dilution gauging (Figure 9) consists of injecting a **tracer** in solution into the watercourse and monitoring its concentration over time. When the condition of good tracer mixing is ensured - and if there is no loss of water in the dilution basin - by **mass conservation law**, the dilution factor is directly proportional to the flow of the river. Several generations of tracers have been historically used, the current state of the art being to favour **fluorescent tracers** (rhodamine, uranine) or cooking **salt**.

3.3. Linking height and flow: the calibration curve

The most **delicate** link is the **setting curve, the** relationship between height and flow (Figure 10)**.** For a long time manually drawn, according to the operators' expertise alone, the definition of this curve now calls for **decision support tools**, tools combining statistical approaches, taking into account metrological uncertainties on gauging, hydraulic models.

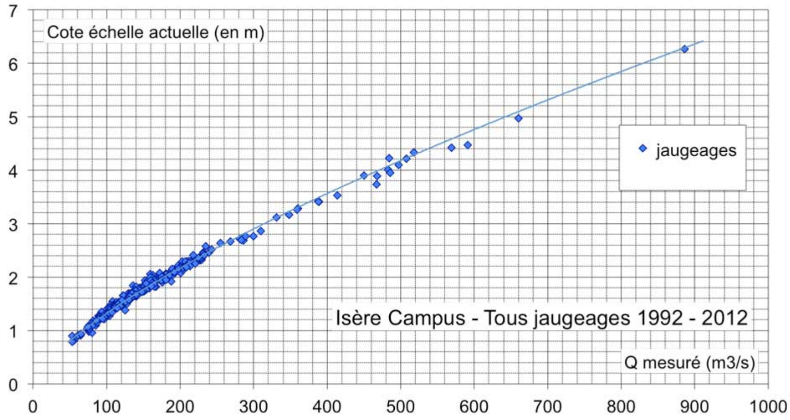

Figure 10. Taring curve of the Grenoble Campus station. For most river stations, the setting curve can change for multiple reasons and never tends - as a general rule - towards stabilization. Here at Grenoble Campus, the calibration curve shown is the one valid between 1992 & 2012. It was then modified due to work carried out on the Isère dikes from September 2012. The curve evolves rapidly until April 2013 and seems to have stabilized again since. [© LTHE, now IGE]

The height-flow relationship, if it is considered stable over a given period of time, is **not necessarily** stable over **time, especially when the hydraulic control is not constituted by an artificial structure**. Vegetation, human intervention, flooding - through the associated mechanisms of solid transport, erosion or deposition - more or less often modify the flow profile of the river. Monitoring the setting curve thus conditions a real **gauging strategy**, to be adapted both temporally (frequency of gauging) and according to water conditions (low water, average water, floods). Monitoring and plotting the calibration curve is the **core business of hydrometry**.

The state of the art has recently evolved with indwelling devices that allow **continuous speed measurement**, either **on the surface** (speed radar) or indwelling in the flow **(**transit time **ultrasound** or Doppler effect). The principles of hydrometry are not fundamentally changed: a **calibration relationship of height, velocity(s), flow rate remains to be calibrated** throughout the operation of the measurement site. These systems were already implemented when a unique relationship between height and flow was not verified (rivers regulated by navigation and/or subject to tide), but current technological developments make it less costly to distribute this type of installation.

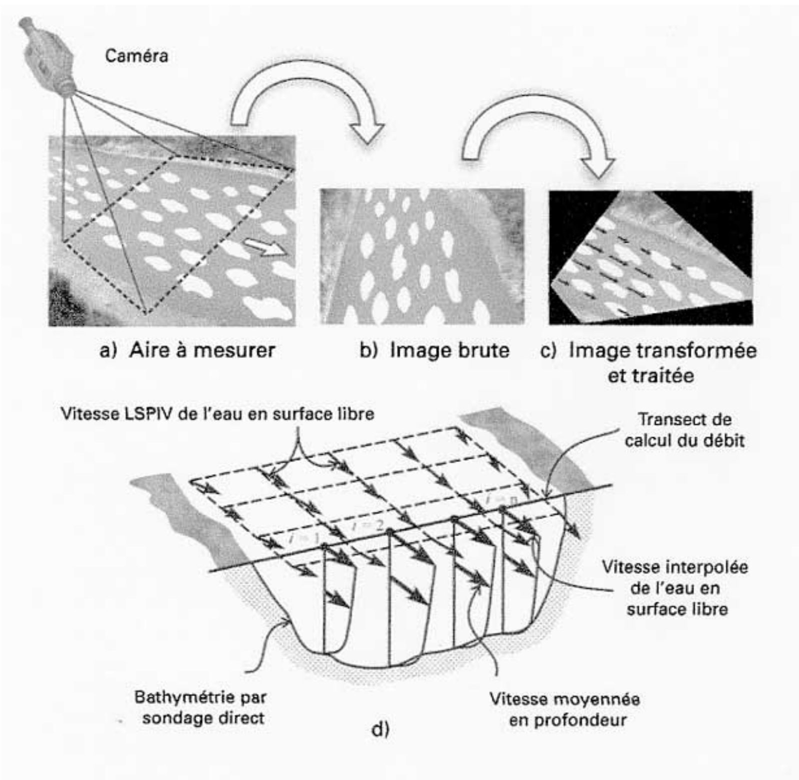

Figure 11. LSPIV principle: a) seeding of floating bodies, b) image recording, c) ortho image rectification, d) flow calculation from LSPIV surface velocity measurements (from Muste)

New imaging technologies bring a promising innovation: **video image processing** to determine the field of **surface velocities of** a river (Figure 11). We use here the **displacement of all solid bodies** transported on the surface (twigs, bubbles, leaves...) as well as the **turbulence of the flow**. This technique is derived from the *Particle Image Velocimetry (PIV*) used in the laboratory, but for a study on large-scale river-type objects, hence its name *Large-Scale PIV (LSPIV*). This includes:

recording **time-stamped image sequences of** the flow,

a **geometric correction of** the images to avoid perspective distortions,

a **calculation of the displacement of** the flow tracers using a statistical analysis in correlation with the patterns.

Knowing the geometry of the river section and assuming a vertical velocity distribution model, the **total flow** is estimated from **the LSPIV velocity field**.

This technique of the future opens the way to a **densification of flood measures**: the fleeting nature of the episodes, the difficulties of access (flooded roads), the security conditions (violent flows) not allowing the teams to intervene as much as necessary. However, it cannot yet be implemented in case of **poor visibility** (night, fog).

3.4. Check the consistency of the data

The **conversion of heights into flow, the critique of the results, the archiving in the database** are the last part of the hydrometry business.

Consistency tests are carried out on the **recordings at the station** (identification of shifts & sensor drifts, smoothing of the raw signal, filling in gaps over recording failure periods) and by more or less sophisticated **hydrological models**:

in **coherence with other** upstream and downstream **measurement sites**,

with **reference to historical data** already compiled at the measurement site, by comparing it with previous years, looking for explanations based on the measurement of rainfall, known influences (water withdrawals, etc.)

The whole process is iterative, and therefore can lead to **questioning** the current calibration curve and thus redefine its layout, or even the calibration strategy. Information obtained **long after the occurrence of** the hydrological **event** (hydraulic modelling, flood gauging,...) can lead to significant changes in the results published at a station. It is common to allow a period of **eighteen months to two years** for the consolidation of information.

The **quantification of uncertainties** in hydrometry has progressed considerably in recent years, but remains an **area of investigation** for the profession. It is considered that on the best stations (i.e. those where the calibration curve can be followed at a rate of less than 4 or 5 gauges per year), the current flows - encountered 80% of the time - are consolidated to within **5%**.

4. What are the current challenges for hydrometry?

Let us keep in mind that hydrometry is a **labour-intensive process**, which requires travel in the field and is a real **craftsman's task** combining metrology, hydraulics and hydrology. As a result, the **annual operating cost of a station** is often in the order of magnitude of the **initial investment cost** to create the measurement point. Hydrometry is therefore a **long-term** task, where budget cuts have a major impact on the quality of the data produced.

Hydrometry is also a **complex** process, as it affects the natural environment, with all its associated hazards, and where the **maturation times of the data can potentially be long**. Thus, between information given on the spot (or even used to make a decision) and consolidated data after criticism or discovery of new elements, **significant** differences may appear **(twice as much** for an extreme regime value, in flood or drought) several years after their occurrence.

Finally, hydrometry is a **process in** the making: the availability of new **imaging** (LSPIV) and **communication technologies** (telephony, internet) will increase the flow of collected data. Questions will quickly arise about the **processing of this information**, its **criticism and homogenization**, its **conservation**, and the **skills** that accompany this massification of information. All this is in response to a real social demand for a **better knowledge of the environment**, a **reduction in vulnerability** to hazards, in the current context of climate change and the preservation of biodiversity.

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