Accuracy in water losses estimation in the distribution network – the Paris case

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Abstract The yield of a distribution network represents one of the indicators most commonly used by water distributors to account for the state of the volumes of losses over a given period or to measure the evolution of these losses from one year to the next, generally speaking. However, contrary to what might be thought, complex situations and very differing interpretations are to be found on the back of the result of the calculation of the volumes of water lost in the distribution network. A study of drinking water network yield was carried out in Paris in 2001 so as to get a better grasp of the developments recorded since 1987. The consequences of the changes that have taken place during this period have each been measured: alterations to the organisation of the water system, developments affecting the structure of the supply system, technical improvements in the wholesale water metering systems and overall reduction in volumes consumed.

Keywords Accuracy; distribution network; water losses; yield

Introduction
Transportation of the drinking water required for the supply not only of domestic consumers, craft trades and industry but of all other municipal needs is an activity that cannot fail to include a certain volume of losses. These lost water volumes can be expressed in different ways, be it in m$^3$ per km of pipes, as a percentage of the volume initially introduced into the network or again by taking into account the number and type of service pipes. In this area, the great deal of work carried out, particularly within the IWA, has advanced and continues to advance our thinking.

Regardless of the method of calculation chosen, these indicators are valuable both with a view to reporting on the state of a distribution pipe network at a given moment in time and, above all, to setting oneself specific objectives when the resource is limited. The economics of the problem are a vital factor and decision-makers are frequently confronted with a dilemma when having to choose where to make their investments: are they to increase the capacity of the resource (production) or to improve efficiency in the use of the existing resource (distribution)? An estimation of water losses and the potential gains that can be expected from a campaign to combat leaks enables one, generally speaking, to resolve the issue. The whole point is whether a given level of water losses is acceptable or not under the technical and economic conditions encountered.

There are however a number of factors of uncertainty that need to be taken into account when calculating water losses. These uncertainties are mainly based on the determining of the volumes introduced (metering devices and related precision) and consumed (method of readings, estimations, age of meters, etc.). The particular conditions pertaining to a given distribution network, together with the definition itself of losses or changes in the price of water and consumption can also exert a not inconsiderable impact.

Furthermore, changes in these methods of calculation and recourse to new technologies may also introduce on a one-off basis increases or reductions in the volumes of water losses calculated, without for all that reflecting the reality on the ground.

Lastly, there exist numerous types of water management organisations that can be associated with mandatory results in the matter of water loss control. The importance attached
to the uncertainties surrounding calculation of the latter can in that case reach beyond the
technical boundaries and touch on economic (water price) and contractual (breach of con-
tract) aspects.

Paris water system
Paris, the capital of France, is a city of 2 million inhabitants where 4 million people live and
work during the day. The average daily consumption of drinking water in Paris is
670,000 m³.

The municipal service of water in Paris is more than 140 years old. In 1985, the Mayor of
Paris decided on a vast renovation program of the means of production and the distribution
system. It started with the privatization of the distribution: two private distributors were
created in Paris, CEP (Compagnie des Eaux de Paris) on the right bank of the Seine river
and EF-PE (Eau et Force – Parisienne des Eaux) on the left bank of the Seine river. These
two companies are responsible for water distribution and invoicing the consumers.

In 1987 the City of Paris completed its reorganization of the water system by creating
SAGEP (Société Anonyme de Gestion des Eaux de Paris), a private/public company in
which it retains 70% of the shares. SAGEP produces drinking water and transports it to the
capital. In addition, SAGEP is responsible for the water pressure and water quality in the
distribution system. Extensions of the water networks in Paris (newly laid pipes) and super-
vision of the two distributing companies for the city of Paris are also part of SAGEP’s
responsibilities.

Uncertainties generally associated with yield
Calculation of the volume introduced
A precise calculation of the volumes of water produced fails to offer any particular interest
for the large majority of operators. For this reason, in many cases, the volume introduced is
calculated indirectly by the volume sampled at source modified by a set coefficient, or else
by the aggregated working time of the recirculating pumps at the production outlet level.
Uncertainties or biases (depending on the method of assessment of the pump flow) in
excess of –10% are quite possible. The latter system was in force in Paris until 1987.

Calculation of the volumes consumed
A wide variety of cases exists. These are frequently linked to the way in which the amount
of water consumed is billed. This can be free of charge or estimated on a provisional-sum or
true basis according to the indication provided by a meter. Moreover when, in the best-case
scenario, one has access to consumers’ meters, the volumes billed offer an uncertainty as to
their allocation over time. This is due to the method employed for meter reading. Water
bills are generally based on an estimation cycle with subsequent adjustment. The index
readings in Paris are generally carried out every six months for “normal” consumers and
every three months for “large-scale consumers”. It is therefore no easy matter to define con-
sumption over a precise period. This would only be possible if, on one and the same day,
one were able too read all the 90,000 meters in Paris. On the other hand, any errors should in
all logic be compensated for over a period of several consecutive years.

In simple calendar terms, one day’s reading in advance or behind time comes down to
±0.3% with regard to yield (±1/365).

It is generally admitted that users’ meters which measure consumption drift progres-
sively over time towards under-metering, which is reflected in a “natural” deterioration in
yield as a function of the age of these meters. Depending on the service and maintenance
conditions, this estimated under-metering is very variable and could be situated between
–3% and –15% after a period of twenty or so years. The average age of the meters in Paris is
slightly more than 9 years. This has been reduced but it is not certain that the new meters age better than those of the previous generation.

Definition of the volume consumed
The volumes of service water (used in fire-fighting, sprinkling and cleaning and rinsing of pipes during special events, etc.) may or may not be considered as volumes consumed and thus be accounted for when calculating yield. Generally speaking, as regards a large distribution network, it is almost certain that occasionally not inconsiderable volumes fail to be taken into account and thus mistakenly appear as leaks. The volume of losses not attributable to leaks has been estimated at between 1% and 2% in Paris. In the case of Paris, since the pipes are located in tunnels or sewers frequented by various operators, it is quite common for companies to clean these tunnels and sewers by opening up the drains. When drains are found to be open, the distributor closes them. Very often, however, uncertainty remains as to the date when they were opened which makes it difficult to calculate the volume of water lost. By way of example, the effect of the opening of 6 drains on the right bank of the Seine in 2001 has been estimated at 566,000 m³ or 0.35% of its yield.

Due to these uncertainties, it is an illusion to attach too much importance to precise measurement of yield: the second figure after the decimal point corresponds in fact to a hundreth percent (a ten thousandth) while the accuracy of the calculation of the volumes introduced and consumed is at best generally speaking a few fractions of a per cent.

Since 1987, drinking water network yield in Paris has evolved with periods of increase and decrease (see Figure 1). These variations can be genuine following a reduction or rise in the volume of water losses, or else induced as indirect consequences of the changes occurring either in the systems for metering the water distributed or consumed, or in the consumption itself.

One may note in Paris that:
• the system for metering the volumes consumed (users’ meters) has changed little since 1987;
• Parisians’ consumption saw a sharp fall between 1990 and 1998 (–17.1%) followed by a slight recovery in 2000 and 2001 (+0.85%);
• the system for metering the volumes distributed (wholesale water metering) has experienced several important phases of development in three stages in 1989, 1992 and 2000–2001.
The evolution of water losses must then be estimated on the basis of these considerations.

Variations in consumption
Variations in consumption lead automatically to a variation in yield expressed as a percentage. This phenomenon is familiar to water distributors. For the year 1990, the volume of drinking water distributed in Paris came to 302,774,000 m³ for a volume consumed amounting to 255,238,000 m³, that is to say a yield totalling 0.843. From 1990 to 1998, the volume consumed subsequently recorded a fall of –17.1%, i.e. 43,655,000 m³. If the leak volume had remained stable over the same lapse of time, the new yield linked to the fall in consumption would have been:

\[
\frac{255,238,000 - 43,655,000}{302,774,000 - 43,655,000} = 0.817 \text{ or a fall amounting to } -2.6\%
\]

In reality, the accepted yield for 1998 is 0.897 which corresponds to an improvement in comparison with 1990 amounting to +5.4%. The actual increase in yield between 1990 and 1998 is therefore around +8%. This is confirmed by the reduced volume of losses. From 47,536,000 m³ in 1990, the figure dropped to 24,297,000 m³ in 1998.

Architecture of the wholesale water metering system in Paris
The wholesale water metering system in Paris (see Figure 2) breaks down into two families of measuring devices.

So-called peripheral meters, known as D. 18 in number, they are positioned at every intake point in Paris with the aim of recording the sum total of volumes distributed.

The transfer meters, known as P. These also number 18, and are in position on all the pipes crossing the Seine with a view to recording the sum total of volumes passing from one bank to the other. The Ps complement the Ds in order to establish a distinction between the volumes distributed on the right bank and those distributed on the left bank.

**Figure 2** "D" and "P" meters
The drinking water supply for Paris is such that two thirds of the means of production (Ivry, Orly, Vanne and Loing) are situated on the left bank of the Seine ($W_G$) and one third (Joinville and Avre) on the right bank ($W_D$) while, conversely, consumption breaks down into two thirds on the right bank versus one third on the left bank. Consequently, the Ps ($W_T$) make up on average one third of the total volume distributed ($W_D + W_G$) and originate from the left bank ($W_G$). It is therefore fair to say that “one third of the water is metered twice in Paris (in $W_G$ then $W_T$)”.

In 2001, the D and P wholesale water meters recorded 346,846,200 m$^3$ while the volume officially distributed throughout Paris was only 249,040,300 m$^3$. Possible metering errors are thus applicable to volumes greater than those billed or distributed. This fact tends to lower the accuracy of the volumes distributed on the left bank compared with those distributed on the right bank (by reason of the direction taken by the water as it flows under the bridges: from the left bank to the right bank). For all that, one is not in a position to say that there is a financial advantage or disadvantage for EF-PE. An inaccuracy of 1% in relation to the volume recorded (3.47 Mm$^3$) concentrated on the Ds results in an inaccuracy of 1.4% in relation to the volume distributed (3.47 divided by 249).

**Influence of the structure of production on yield**

The influence of the structure of production, that is to say the breakdown between the distinct production units, is doubled in Paris: the first consequence by reason of the method of calculation chosen with regard to EF-PE yield; the second consequence is due to the dispersion of the metering errors over the D and P flow meters, as well as to the distribution of the volumes recorded on these meters.

Depending on the way one looks at the volume of $W_T$ transfer; namely as a volume consumed or otherwise, the yield value for EF-PE will be perceptibly different. If $W_T$ is considered as a volume consumed, the volume actually billed on the left bank in Paris has to be added to volume consumed on the left bank ($V_G$). The yield is then:

$$\frac{V_G + W_T}{W_G}$$

If $W_T$ is not considered as a volume consumed (official method of calculation), the volume introduced on the left bank must be subtracted from $W_G$. The EF-PE yield becomes:

$$\frac{V_G}{W_G - W_T}$$

For 2001,

- $V_G = 68,524,885$ m$^3$
- $W_G = 179,313,200$ m$^3$
- $W_T = 97,318,300$ m$^3$

The yield for EF-PE over the year 2001, if $W_T$ is considered as a volume consumed, is 0.925. The yield for EF-PE over the year 2001 if one considers the official method of calculation is 0.836. The difference in yield between these two methods of calculation is considerable (8.9%) and increases when $W_T$ rises.

The diversity of resources (springs and plants) and the potential production reserve (overcapacity) are important factors as regards the safety of the drinking water supply to Paris. This situation permits scheduled shutdowns of production centres while works are being carried out. At the same time, a satisfactory safety margin is preserved.

One may thus observe throughout the year revolving shutdowns of the means of production (for example, the shutdown of the Orly plant during the summer of 2001). On the occasion of these production stops, the structure of the Paris drinking water supply is modified. This is reflected in a transfer of production to other centres (in the summer of...
2001, the Ivry and Joinville plants produced more than usual). These transfers of produc-
tion result in a different breakdown of the volumes measured by each D and P flow meter.

Now if the accuracy of the meterings is $\pm 1\%$, the 36 D and P meters certainly do not all
individually present the same accuracy. This means that on the occasion of a change in the
structure of production, it is possible that part of the volume distributed may be shifted from
a meter possessing an accuracy of $-1\%$ to a meter possessing an accuracy of $+1\%$.
Unfortunately, the only time one knows the accuracy of a flow meter is after it has under-
gone testing on the test bench. It is therefore very difficult to estimate the metering discrep-
ancies produced by the changes in the structure of production.

Furthermore, the accuracy of a metering point varies as a function of the flow recorded;
these variations are generally slight but have an impact all the same. For this reason, the
adjustment of the flow meters on the test bench is carried out on several flow ranges. The
increase in the volumes measured on the flow meters associated with the centre benefiting
from a transfer of production is likely to produce discrepancies in the volumes distributed
and therefore in the yield.

A change in the structure of production can lead to metering discrepancies that repre-
sent, on the one hand, the consequence of the differences in accuracy between the meters
and, on the other, the variability in this accuracy as a function of the flow.

Changes in the system of wholesale water metering in Paris from 1987 to 2002

The changes made to metering of wholesale water all meet a dual objective:
• to better measure the volumes of water (in a fairer way);
• to permit verification of the accuracy of the measuring devices (calibration).

These changes concern:
• either the measuring device (technology, electronics, etc),
• or the hydraulic service conditions (results of working-over of pipes),
• or the location of the measuring device (shift up- or downstream).

On the occasion of any change or modification of the whole or part of the metering
system, an interruption is introduced at the level of the historical record of the yield. This is
reflected in a sudden and more or less noticeable shift upwards or downwards, depending
on circumstances. It is possible in theory to erase this stair-shaped shift by rectifying the
volumes measured prior to the change in the discrepancy observed between the old and the
new system. In practice however, this rectification does not prove to be particularly valid
over a long period in as much as the discrepancy observed (when known) represents a given
point in time and cannot be extrapolated over long durations without running a risk. The
main developments in the wholesale water metering system have been as follows.

At 1 January 1989

Switchover from the old metering system in force at the time SAGEP was set up (and which
was based, in the production centres, on a calculation of the operating time of the booster
pump sets and on venturi flow meters), to the new metering system using the Ds. The old
system presented an overall under-metering amounting to $-3.02\%$ compared with the new
Ds-based one. This average discrepancy conceals relatively marked differences. The
new system possessing as it does a reputation for greater accuracy, the volumes
distributed before 1989 were underestimated by $-3.02\%$ and the official yield values were
consequently overestimated by approximately $+3.02\%$.

This switchover was accompanied in accordance with the provisions laid down in the
contract, by a change in the basic price of wholesale water. It can then be asserted that
between 1988 and 1989, an interruption occurred in the historical record of yield in Paris
(see Table 1).
At 1 January 1992

Coming onstream of the Ps metering system. This development was also scheduled in the programme in 1987 and mentioned in the SAGEP licence agreement. The consequences of this switchover do not in theory result in any sudden variation in the value of overall Parisian yield since the only problem consists in separating left bank from right bank yield. In reality, the fact that one has at one’s disposal distinct efficiencies makes it possible to compare the performance levels achieved by the two distributors and to benefit from the direct consequences for sales of wholesale water.

Prior to 1992, the wholesale water bill was spread between the two distributors in proportion to users’ consumption on each bank, on the supposition that the yield was identical on each side of the Seine. From 1 January 1992 on, the distributor who had achieved the greater yield found himself at an advantage due to a fall in his volumes bought from SAGEP whereas the other distributor received the reverse treatment.

The switchover of the Ds on 1 January 1989 went off with no problems in as much as the financial consequences were ironed out by the adjustments in the price of wholesale water provided for in the contracts with the City of Paris. On the other hand, the switchover of the Ps was immediately reflected in a loss for one of the distributors and a strictly equivalent gain for the other.

The period of observation of the transfer recordings prior to the switchover led to doubts being expressed about the quality of the P meters by the distributor who would have found himself at a disadvantage. The proposal that the Ps be switched over on 1 January 1990 was therefore postponed in the absence of an agreement between the parties. The deadlock was only broken by recourse to an outside expert report which was carried out in the course of 1992. On this occasion, the service conditions of all the meters (D and P) were reviewed and heavy equipment (temporary installation of current meters in the pipes) was put in place so as to assess the accuracy of the meterings.

The conclusions of the arbitral expert report made it possible to:

- adjust the metering system with a view to greater accuracy (regulation of the sensors and modification of the parametering of the flow meters);
- estimate the metering error prior to the adjustments, i.e. an over-metering of the Ps by +3.2%;
- to provide an estimation of the accuracy of the wholesale water metering system in Paris, i.e. ±2% per meter and ±1% overall, which was remarkable;
- to take into account retroactively and with the necessary corrections the P data from 1 January 1992 on.

During the discussions between SAGEP and the distributors and subsequently during the arbitral expert report (from 1990 to 1992), water losses in the distribution networks balanced out.

The making possible of a comparison between the yield of each of the distributors (see Figure 3) and billing the volumes actually introduced on each bank therefore produced, as an indirect consequence of the switchover of the Ps, a very marked and genuine improvement in overall yield in Paris: from 79.8% in 1989 to 89.9% in 1992.

### Table 1 Adjustment to historical record of yield in Paris

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<tr>
<td>Gross yield</td>
<td>81.4</td>
<td>80.4</td>
<td>81.8</td>
<td>79.8</td>
<td>84.3</td>
<td>88.1</td>
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<tr>
<td>Corrected yield</td>
<td><strong>78.4</strong></td>
<td><strong>77.4</strong></td>
<td><strong>78.8</strong></td>
<td>79.8</td>
<td>84.3</td>
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B. Nguyen
From 1992 to 1997

The technological advances in the field of flowmetering are reflected in the wholesale water metering system, the concern being as ever to achieve the greatest possible accuracy and reliability. In 1985, ultrasonic flow meter technology was chosen by common accord between SAGEP and the distributors. The ultrasonic equipment offered the advantage of being easy to install without the need to change the pipes fittings and at a cost that was not dependent on the diameter of the pipe. On the other hand, ultrasonic flow meters tend to under-meter when flows are low and require that special precautions be taken when their location is chosen. Moreover, the possible on-site adjustments do not provide the quality of calibration on a laboratory test bench.

For certain metering points where the hydraulic conditions were not conducive to standardised use of an ultrasonic flow meter, preference was given to another electromagnetic technology from the start of metering in 1985. Installation of an electromagnetic flow meter is more complex since it is necessary to cut a piece of the pipe so as to place the measuring device inside. This is offset by the fact that the measurement provided is less sensitive to the hydraulic conditions than an ultrasonic flow meter. The cost of the electromagnetic flow meter is proportional to the diameter of the pipe and it is possible to dismount the equipment for purposes of verification and adjustment on a test bench.

After 1992, the electronics of ultrasonic flow meters went digital and were gradually replaced. These modifications provided greater stability of measurement without for all that markedly affecting yield. In 1998, there were 29 ultrasonic flow meters in existence and 7 electromagnetic flow meters.

From 1999 to the present day

At the end of 1997, SAGEP and the distributors agreed to replace the ultrasonic flow meters by electromagnetic flow meters. Electromagnetic flow meters are subjected to a programme under which they experience the test bench at the SAGEP metrology laboratory. Calibration enables one to validate an error of measurement expressed as a percentage for the average flow observed on the flow meter. Should this error exceed the admissible limit, one has then to correct retrospectively the wholesale water bills by going back in time to the most recent calibration. The flow meter is then adjusted prior to being repositioned. The “large” metering points are verified every year and the “small” ones every two years.

The volumes measured are thus definitively validated a posteriori after verification on a test bench with, if necessary, a readjustment of the bills. The accuracy of the SAGEP test bench is ± 0.20%; any equipment presenting an error greater than ± 1% is scrapped.
The calibration process is described in detail in a manual validated by SAGEP and the distributors.

The replacement of ultrasonic flow meters by electromagnetic flow meters was concluded in late 2002. The new devices had on occasion to be shifted in relation to the old (the resulting yield data is shown in Figure 4) (and overall water loss data in Figure 5). In certain cases, one was able to compare the discrepancies between electromagnetic flow meters and ultrasonic flow meters. In all cases, the new meterings are reputed to be better than the old and cannot be challenged over a period validated between two bench calibrations.

The average impact recorded in Paris on the occasion of the replacement of an ultrasonic flow meter by an electromagnetic flow meter between 1999 and 2002 was +1%, that is to say in the direction of an increase in the volumes measured.

**Conclusion**

The factors that influence yield are numerous. When yield evolves, these factors can have considerable importance if economic consequences, set down in the licensing agreements for distribution of the water, are associated with them (water price pegged to yield).
structure of the Paris drinking water supply has direct consequences on the calculation of its official value.

Between the beginning of 1987 and the end of 2002, yield from the drinking water distribution networks in Paris underwent a definite evolution in a particularly unstable context: a dual modification in the metering system (integration of D then P flow meters), successive technological developments and a marked fall in consumption.

There can be no doubt that the accuracy and reliability of the wholesale water metering system have greatly improved in Paris. However, the most suitable indicator for monitoring the improvement or actual degradation of the water pipe networks is not the yield. The annual volume of losses on the other hand seems much less unstable and is not subject to as many possible interpretations. It probably represents the simplest and most reliable indicator for monitoring changes over time in the Paris drinking water network but it cannot be used for the purpose of making comparisons between one town and another.