Water and Energy Efficiency in Bulk Water Systems

Laura Monteiro[1], Aisha Mamade[2], David Figueiredo[3], Rita Alves[4], Pedro Póvoa[5], Dídia Covas[6]
[1,2,6] CERIS, Instituto Superior Técnico, Lisbon, Portugal
[3,4] Research, Development and Innovation Unit, Águas do Tejo Atlântico, Lisbon, Portugal
[5] Asset Management Unit, Águas do Tejo Atlântico, Lisbon, Portugal
[1] *laura.monteiro@tecnico.ulisboa.pt*

ABSTRACT

Water losses and energy efficiency in supply systems is an actual concern for utilities. While the methodologies for water losses and energy efficiency assessment have been developed, their application in bulk water supply systems is limited. This paper provides data on water losses levels and energy efficiency performance of three Portuguese bulk water supply systems that can be benchmarked with similar systems worldwide. In addition, it points out major uncertainties in water balances calculation in such systems and identifies constraints in applying the methodology. The usefulness of computing the energy balance for efficiency assessment in bulk supply systems is demonstrated.

Keywords: Water Balance, Energy Balance, Bulk Water Systems

1 INTRODUCTION

Water supply utilities are currently faced with the need to manage their systems as efficiently as possible, in order to ensure their long term economic and environmental sustainability. Hence, water losses minimization alongside with a more rational use of energy is necessary. Traditional reactive approaches, based on bursts repair and on inefficient equipment's replacement, are not effective. Water-energy losses management plans must be developed, on which well-defined goals must be set and suitable measures for improvement must be clearly identified [1]. Such requires a complete characterization of the actual water losses and energy consumption performance of the whole system.

Standardized water balances for supply systems have been established [2] to assess water losses. The methodology includes the calculation of a set of performance indicators (PI) [3] and of water losses components (real and apparent). Establishing a water balance is straightforward and tools for its calculation have been developed. The methodology is most usually applied for the whole water supply system on an annual basis [4] and allows water utilities to monitor water losses evolution over time.

The energy balance was only recently developed [5]–[7] and its application to real systems, so far, is limited [1]. The energy balance approach is similar to the water balance one and is based on the calculation of energy inputs and consumption/dissipation components. It allows the identification and quantification of main energy inefficiencies associated with water losses, pumping, operation modes or system layout [6].

This paper presents the main results from the assessment of water losses and of energy efficiency in three bulk water supply systems in Portugal by applying the water and energy balances. It describes the advantages and limitations of these methodologies to accurately assess water losses and energy efficiency and highlights the particularities of their application to bulk supply systems.

2 METHODOLOGY

2.1 Case studies description

Three bulk water supply systems of different characteristics were studied (Table 1). The systems transport water from treatment plants (Cases A and B) or from upstream bulk systems (Case C) to municipalities, who ensure distribution of water to downstream consumers. Case study A is located in a touristic area and must comply with demand volumes in summer that are 5 times higher than in winter. Case study B is a small system located in a hilly area. System C is a large water transmission system almost completely dependent on pumping. Systems A and B are supplied by gravity and include pumping to part of the delivery nodes. Water flow is continuously measured at all input and delivery nodes. Hydraulic models have been previously developed for these systems.

Table 1. Case studies characteristics

System	Lenghth of mains (km)	Range of mains diameter (mm)	Number of delivery nodes	Number of Pumping stations	Number of storage tanks	Annual input volume (m^3)
A	110	1200-125	18	13	2	19,375,050
B	18	1000-150	9	4	5	5,060,384
C	94	200-600	22	7	7	9,774,784

2.2 Water losses and energy efficiency assessment

For the water balance calculation, data on annual input volumes, billed metered consumption and unbilled authorised consumption volumes when available (case studies A and B) were collected. Water balances components and PI calculation were performed using a Microsoft Excel spreadsheet according to the standard procedure [2]. Average measurement errors were provided by the utilities.

For the energy balance, a C++ computational tool was developed for computing all the components of the energy balance based on the hydraulic models developed in EPANET for the three case studies. Thus, all assumptions and simplifications of the models are included in energy balances results (e.g., constant pump efficiency throughout time). For all cases, the hydraulic models used were developed for average annual water consumption scenarios. The energy balance methodology adopted was that from [6]. A set of PI were calculated for each case study and compared with reference values set by the Portuguese Water Regulator (Ph5) or with provisional reference values.

3 RESULTS

3.1 Water balance components

Figure 1 presents the annual water balances results for the three case studies (A, B and C).

<table>
<tr><td rowspan="9">System input volume
27,344,597 (A)
4,988,045 (B)
9,774,784 (C)</td><td rowspan="4">Authorised consumption
26,898,392 (A)
4,979,287 (B)
9,631,567 (C)</td><td rowspan="2">Billed authorised consumption
26,896,594 (A)
4,967,723 (B)
9,631,567 (C)</td><td>Billed metered consumption
26,896,594 (A)
4,967,723 (B)
9,631,567 (C)</td><td rowspan="2">Revenue water
26,896,594 (A)
4,967,723 (B)
9,631567 (C)</td></tr>
<tr><td>Billed unmetered consumption
0 (A)
0 (B)
0 (C)</td></tr>
<tr><td rowspan="2">Unbilled authorised consumption
1,798 (A)
11,564 (B)
0 (C)</td><td>Unbilled metered consumption
1,798 (A)
5,764 (B)
0 (C)</td><td rowspan="7">Non-revenue water
448,003 (A)
20,322 (B)
143,217 (C)</td></tr>
<tr><td>Unbilled unmetered consumption
0 (A)
5,800 (B)
0 (C)</td></tr>
<tr><td rowspan="5">Water losses

446,205 (A)
8,758 (B)
143,217 (C)</td><td rowspan="2">Apparent losses

136,723 (A)
4,988 (B)
48,158 (C)</td><td>Unauthorised consumption
0 (A)
0 (B)
0 (C)</td></tr>
<tr><td>Metering inaccuracies water losses
136,723 (A)
4,988 (B)
48,158 (C)</td></tr>
<tr><td rowspan="3">Real losses

311,280 (A)
3,770 (B)
95,059 (C)</td><td>Leakage on transmission mains
311,280 (A)
3,393 (B)
95,059 (C)</td></tr>
<tr><td>Leakage and overflows at transmission storage tanks
0 (A)
377 (B)
0 (C)</td></tr>
<tr><td>Leakage on service connections up to the measurement point
0 (A)
0 (B)
0 (C)</td></tr>
</table>

Figure 1. Water Balances for the three case studies (m3/year).

A common feature of the three balances is the inexistence of the billed unmetered consumption and unauthorized consumption components. In addition, only utility of system B estimated unbilled unmetered consumption volumes.

The inexistence of billed unmetered volumes indicates that the balances are mostly based on metered volumes instead of estimated ones and, thus, increases the reliability of the balance. Contrarily, the lack of unauthorized consumption component suggests that the utilities do not know how to determine this component or are not aware of possible illegal uses of their water. While a rule of thumb of 0.25% of the system input volume could have been used [8], further efforts should be made to identify and quantify possible water thefts.

Unbilled authorized consumption volumes are mainly due to the utilities own consumption (e.g., for cleaning storage tanks and flushing pipes). The value provided by utility A is insignificant when compared with the systems' input volume, however, the one obtained for Case B is in the same magnitude of the estimated water losses (Figure 1). This suggests that although measuring or estimating water volumes consumed in maintenance operations is currently recommended for water loss control [8], its importance for an accurate calculation of the water balance is higher for smaller systems than for larger ones.

Real losses calculation entails an estimation of apparent losses, which in these case studies are assigned to meters' inaccuracy. A good estimation of apparent losses would require to know each meter measurement error. However, in large diameter transmission pipes, as the ones in these case studies, it is not possible to assess the meters' error in the actual operating conditions. Hence, global average errors were assumed, as in other studies [4]. Such denotes a considerable uncertainty in real losses quantification.

A common difficulty among the three utilities was to identify the components of the real losses, as the estimated values are not currently crosschecked with any other available data (e.g., water volumes lost in bursts). While utilities A and C assumed real losses associated uniquely to leakage volumes on transmission mains (Figure 1), utility B used a rule of thumb of 90/10, where 90% of the real losses is due to leakage in mains and 10% is due to leakage and overflow in storage tanks.

3.2 Water losses

Non-revenue water, as a percentage of the total input volume, varies between 1.4 to 2.0 % (Table 2), which is in the range of a good service level for bulk supply systems. However, for case A, 448 000 m3 represents a significant amount of water lost, that ideally should be minimized for an efficient use of the natural resource, water. In addition, if this water volume is converted into an operational cost, for instance, by assuming a water production cost of 0.5 €/m^3, then 224 000 € are annually spent in this system due to non-revenue water.

Although PI for non-revenue water is low, real losses are quite unexpectedly high, as only Case C exhibits a good service level (Table 2). Given that real losses are calculated as the difference between the total losses and the apparent losses, it is likely that the high real losses obtained are a consequence of an inadequate estimation of apparent losses, particularly for case B.

Table 2.Performance Indicators for water losses.

PI	System			Reference values
	A	B	C	
Non-Revenue Water (%)	1.4 •	2.0 •	1.5 •	• Good [0.0; 5.0]; • Acceptable]5.0; 7.5]; • Unacceptable]7.5; 100[
Apparent Losses (%)	0.5	0.1	0.5	-
Real Losses (%)	0.9	1.4	1.0	-
Real Losses (m^3/km/day)	5.8 •	11.1 •	2.8 •	• Good [0.0; 5.0]; • Acceptable]5.0; 7.5]; • Unacceptable]7.5; +∞[

Hence, besides estimating non-revenue water and ascribing a number to real losses, calculating the annual water balance and the PI using rough estimates of apparent losses does not provide useful information on water losses. For large bulk supply systems, as the ones studied, where non-revenue water is often low and water consumption components are generally measured, apparent losses can be as important as real losses, if not even more relevant depending on the accuracy of the flowmeters. Hence, an accurate estimation of apparent losses must be previously carried, based on a throughout assessment of flow meters measurement errors. In addition, water volumes lost in pipe busts and leakage must be closely monitored and crosschecked with estimated real losses.

3.3 Energy balance components

The complete energy balance allowed to compare the importance of the various components of energy consumption in the case studies. Results obtained for the three systems were similar. Figure 2 presents the annual energy balance results for case study C. Dissipated energy through friction in pipes ranged from 10 to 18% of the total input energy. Pipe friction can account for 1 GWh/year of energy lost (Figure 2). Rehabilitation and/or replacement should take place for energy efficiency improvement. Valve head losses ranged between 0.4 (Case C) and 19% (Case B) and indicated a considerable potential for energy recovery in case B. Surplus energy ranged from 5.8 to 9.7%, suggesting a potential for pressure management in the systems where it is higher. The energy balance components in relation to water losses are very low for the three cases and do not seem to be relevant in bulk supply systems.

<table>
<tr><td rowspan="8">Natural Input Energy
800,974
(11.9%)</td><td rowspan="13">Total system input energy 6,745,708</td><td rowspan="7">Energy associated with authorized consumption
6,658,208
(98.7%)</td><td rowspan="2">Energy associated with water supplied to consumers
4,179,397 (62.0%)</td><td>Minimum required energy
3,581,959 (53.1%)</td></tr>
<tr><td>Surplus energy
597,438 (8.9%)</td></tr>
<tr><td rowspan="4">Dissipated energy due to continuous and singular headlosses
1,308,053 (36.7%)</td><td>Pipe friction
1,016,430 (15.1%)</td></tr>
<tr><td>Valve headlosses
26,651 (0.4%)</td></tr>
<tr><td>Pumping stations' inefficiency
1,435,730 (21.3%)</td></tr>
<tr><td>Micro-hydro power plants' inefficiency
0</td></tr>
<tr><td rowspan="2">Recovered energy
0</td><td>Associated with authorized consumption
0</td></tr>
<tr><td rowspan="6">Energy associated with water losses
87,500
(1.3%)</td><td>Associated with water losses
0</td></tr>
<tr><td rowspan="5">Shaft Input Energy
5,944,734
(88.1%)</td><td colspan="2">Dissipated energy in consumption nodes
45,375 (0.7%)</td></tr>
<tr><td rowspan="4">Dissipated energy due to continuous and singular headlosses
42,125 (0.6%)</td><td>Pipe friction
14,359 (0.2%)</td></tr>
<tr><td>Valve headlosses
0 (0%)</td></tr>
<tr><td>Pumping stations' inefficiency
27,766 (0.4%)</td></tr>
<tr><td>Micro-hydro power plants' inefficiency
0</td></tr>
</table>

Figure 2. Energy Balance for Case study C (kWh/year).

3.4 Energy efficiency

For the overall systems performance assessment, a set of Pi were established (Table 3). E3 values show that the systems are using, on average, the double of the minimum required energy and that the systems that use more shaft power (B and C) are the ones that present the highest E3 values. This is due to relatively low efficiencies of the pumping stations, as the standardized energy consumption (IWA Ph5) among the three demonstration systems is in the range of 0.39-0.48 kWh/ (m^3×100 m) which indicates that the pumps' efficiencies range between 50 and 60%. Thus, the systems' energy efficiency can be improved if more efficient pumps are used. Case A, for which natural input energy is c.a. 70% of the total input energy, requires less pumping and uses more efficient pumps, which is why it is has the best performance in terms of energy in excess per unit of authorized consumption.

Table 3. Performance Indicators for Energy Efficiency.

PI	System			Reference values
	A	B	C	
Ph5-Standarized energy consumption (kWh/(m^{3}x100m))	0.39 •	0.48 •	0.43 •	• Good]0.27; 0.40] • Acceptable]0.40; 0.54] • Unacceptable]0.54; +∞]
E2 – Energy in excess per unit of authorised consumption (kWh/m^3)	0.18 •	0.37 •	0.55 •	• Good]0.0, 0.1]; • Acceptable]0.1, 0.4]; • Unacceptable]0.4,+∞[
E3 – Ratio of the total energy in excess (-)	1.77 •	2.44 •	2.30 •	• Good]1.0, 1.5]; •Acceptable]1.5, 2.8]; • Unacceptable]2.8,+∞[
… associated with natural input energy (-)	1.18	0.63	0.15	-
… associated with shaft input energy (-)	0.59	1.81	2.15	-

Although a certain amount of energy loss is unavoidable for all the systems, and their performance is extremely influenced by the system layout, the energy balance and the PI allowed to trace energy inefficiencies and to identify improvement measures.

4 CONCLUSIONS

The calculation of water balances for three bulk water supply systems allowed to identify major constraints in using this approach for water losses assessment in such systems. Because very low non-revenue water levels are observed, it is very important to accurately determine apparent losses in these systems. Such requires that the flow measurement error is known. Further studies should focus on large diameter flow meters' error assessment.

The energy balance has proven to be an effective tool for determining where and how much energy is dissipated in the systems. Its calculation allowed to identify major inefficiencies and improvement measures.

Acknowledgments

The authors gratefully acknowledge European Commission's LIFE Programme for funding LIFE Smart Water Supply System project (LIFE14 ENV/PT/000508) as well as the water utilities EPAL S.A. and Águas do Algarve, S.A. for providing data.

References

[1] D. Loureiro, H. Alegre, M. S. Silva, R. Ribeiro, A. Mamade, and A. Poças, "Implementing tactical plans to improve water-energy loss management," *Water Sci Technol Water Supply*, agosto 2016.

[2] A. Lambert and W. H. Hirner, Losses from Water Supply Systems: Standard Terminology and Performance Measures. IWA Blue Pages, 2000.

[3] H. Alegre et al., Performance Indicators for Water Supply Services, 3rd edition. IWA Publishing, 2017.

[4] P. Klingel and A. Knobloch, "A review of water balance application in water supply," *J Am Water Works Ass*, vol. 107, no. 7, pp. E339–E350, 2015.

[5] Enrique Cabrera, Miguel A. Pardo, Ricardo Cobacho, and Enrique Cabrera Jr., "Energy Audit of Water Networks," *Journal of Water Resources Planning and Management*, vol. 136, no. 6, Nov. 2010.

[6] A. Mamade, D. Loureiro, H. Alegre, and D. Covas, "A comprehensive and well tested energy balance for water supply systems," *Urban Water Journal*, 2017.

[7] T. Walski, "Energy Balance for a Water Distribution System," presented at the World Environmental and Water Resources Congress, 2016, pp. 426–435.

[8] AWWA, *M36 Water Audits and Loss Control Programs*. American Water Works Association, 2016.

[9] H. Mutikanga, S. Sharma, and K. Vairavamoorthy, "Methods and Tools for Managing Losses in Water Distribution Systems," *J. Water Resour. Plann. Manage.*, vol. 139, no. 2, pp. 166–174, abril 2012.

[10] V. Kanakoudis and S. Tsitsifli, "Using the bimonthly water balance of a non-fully monitored water distribution network with seasonal water demand peaks to define its actual NRW level: the case of Kos town, Greece," *Urban Water Journal*, vol. 11, no. 5, pp. 348–360, Jul. 2014.

[11] L. Andrews, K. Gasner, R. Sturm, G. Kunkel, W. Jernigan, and S. Cavanaugh, "Level 1 Water Audit Validation: Guidance Manual. Project #4639A," Water Research Foundation, Denver, Colorado, USA, 2016.