Extensive analysis of hydraulic parameters in a large set of water distribution systems

P. M. Vidigal & D. I. C. Covas

Instituto Superior Técnico, Technical University of Lisbon (TULisbon), Lisbon, Portugal

D. Loureiro, S. T. Coelho, H. Alegre

National laboratory of Civil Engineering, Lisbon, Portugal

ABSTRACT: A large number of distribution network pipes in Portugal is over-sized for human demand flows, due to regulatory fire-fighting minimum diameters, which has a direct bearing on water quality, given the potentially low velocities it may originate. In order to assess the magnitude of the problem, a large scale study was undertaken, based on twenty water distribution system sectors, from networks across the country, representative of a wide range of conditions. Calibrated hydraulic models developed and updated by the utilities were provided. The extended period models were used for exhaustive runs of typical operational conditions, and the results - flow velocity, pressure, head loss and Reynolds number - were recorded for the sets of time periods concerned. The results were analyzed by using a computer application specifically developed for this purpose. A complete set of statistics for the above parameters was produced. Performance assessment of water distribution systems was also performed based on the results obtained. The main conclusions were that (i) the networks are over-designed with very low velocities in most of the time (due to being designed for the peak flow conditions in 40-year time and for fire-fighting conditions) and (ii) the systems are operated with pressures higher than necessary with evident potential of water losses and energy saving.

1 INTRODUCTION

Water distribution systems are infra structures necessary to support a service to the public health which consists of the distribution of water in quantity and with quality to the populations. These systems are constructed and operated in order to transport, to treat, to store and to distribute water. Traditionally, these systems are designed according technical and hydraulic criteria based on the technical rules, legislation and engineers' good-sense, in order to supply the estimated demand in the following 40 years which is not most of the times achieved. This aspect is very important in water distribution systems because these systems are designed to peak operational conditions (i.e., maximum consumption expected in 40 years time) and with minimum diameters which assure fire protection, which result in over-sized systems with low flow velocities and high water age (Alegre, 1992; Coelho, 1997).

The current research aims at the analysis of characteristic parameters (related to hydraulic and water quality) and performance assessment of water distribution systems in order to investigate how these systems behave during normal operational conditions along the day (Vidigal, 2008). The analysed sectors belong to water distribution systems with varied characteristics and geographic locations, distributed along the national territory. Therefore, these sectors were considered to be representative of the main Portuguese urban areas. A computer application has been developed and implemented to carry out the analysis. The greatest potentiality of this application is to enable the analysis of a great volume of great number of sectors of water distribution systems in a short period of time.

This work initiates with a state-of-the-art review in water distribution domain, including mathematical modelling of these systems and its importance, and review of the most relevant characteristic parameters (hydraulic and water quality). Additionally, it has developed a methodology for the study of characteristic parameters of water distribution systems affecting systems' performance. The computer application developed (using MATLAB programming language) allows the systematic simulation of the operation of the sectors of water distribution systems, considering different consumption scenarios, and performs the statistical analysis of characteristic parameters. The application is composed of three modules: hydraulic simulation, statistical analysis and technical performance assessment. This study also presents the results obtained from a survey conducted with national utilities (out of which 46 utilities replied to the survey), in order to investigate how nowadays mathematical modelling being is ap-

plied to the management of water distribution systems in Portugal. Modelled sectors were analysed with the developed software application in terms of the physical characteristics of the networks (diameter, material, pipe roughness) and the hydraulic parameters (pressure, velocity, head loss, Reynolds number). The study of characteristic parameters' frequency histograms has allowed a better knowledge of the distribution of parameter values in the spatial-temporal dimension of the Portuguese water distribution systems. The most relevant conclusions of this study are taken and recommendations are made towards the review of current design criteria of water distribution systems.

2 STATE-OF-THE-ART

Hydraulic modelling software has being significantly improved during the last years, allowing, nowadays, sophisticated calculations in a short period of time and providing a better knowledge about water distribution system behavior. These tools allow the hydraulic analysis based on the physical characteristics and operational conditions of the systems (Grayman et al., 1988; Cesario, 1995; Mays, 2000; Walsky et al., 2003). Examples of available softwares are Epanet 2.0, AquaNet, H2Onet/map, OptiDesigner, Stanet, Wadiso SA, WaterCAD 5.0.

The "National Programme for Water Distribution Systems Simulation" (INSSAA) was a programme that took place between 2003 and 2006, organized by Civil Engineering National Laboratory (LNEC). The main goal was to provide hydraulic simulation tools and know how to support the management of water distribution systems. There were nine national water utilities involved belonging to different areas in Portugal. Technical guidance and supervision for the construction of the mathematical models of water distribution systems has been given, namely by means of seminars, specialized courses, discussion forums, on-line Web tools and periodic meetings.

The main motivation of this study is the development of a software application (using MATLAB) which allows the systematic simulation of the operation of water distribution systems, considering different consumption scenarios, and performs the statistical analysis of characteristic parameters as well as performance assessment. The application is composed of a hydraulic simulation, statistical analysis module and performance assessment module. The greatest potentiality of this model is to enable the analysis of a significant number of sectors of water distribution systems in a short period of time.

3 NATIONAL SURVEY

A national survey has been carried out within the Portuguese water utilities in order to investigate how the mathematical modelling is being applied in the daily management of water distribution systems in Portugal. This survey was based on an inquiry performed to all utilities, having been obtained 46 replies from the utilities. This survey aimed at better understanding of how far the mathematical modelling of water distribution systems is being used in Portugal. The main conclusions of this survey, summarized in **Figure 1**, are the following:

- 78% of the utilities do not have any type of mathematical model and 22% of the utilities have models of parts of their systems (**Figure 1**a).
- 10 utilities have mathematical models of some systems and only 4 have models for more than 75% of their system (**Figure 1**b);
- one utility (out of the 10 that have mathematical models) started using this tool before 2000 and 5 of those started after 2005 (**Figure 1**c).
- 8 utilities have qualified engineers for constructing, calibrating and updating the mathematical models (**Figure 1**d). This is an important as the model development by external companies does not allow keeping models updated and calibrated.

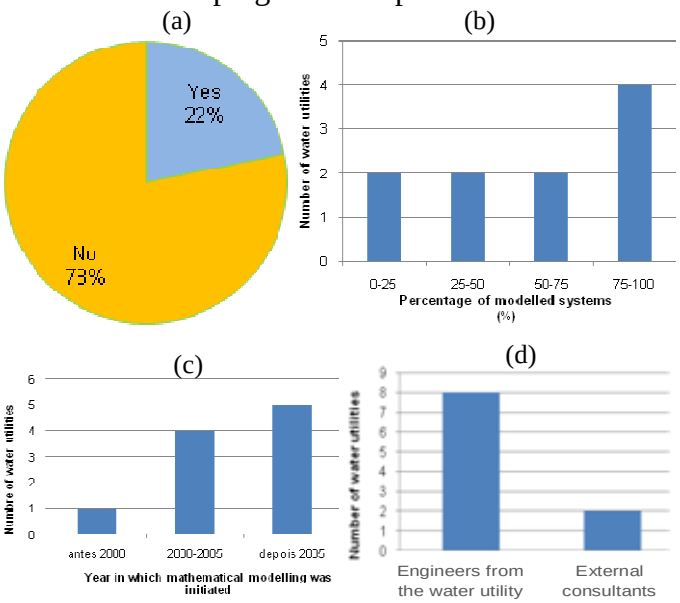


Figure 1 – Survey results: (a) percentage of surveyed systems with (Yes) mathematical models (in a sample of 46 water utilities); (b) percentage of modelled systems which have mathematical models (in a sample of 10 utilities with models); (c) year in which mathematical modelling was initiated (in a sample of 10 utilities with models); (d) who has built and calibrated the mathematical models.

Although, this survey is not representative of the whole Portuguese reality, it allows for understanding the actual situation in the country. The main idea to retain is that the tools available for mathematical modelling must be better disseminated within Portuguese utilities.

4 SOFTWARE APPLICATION

A software application has been developed, using MATLAB programming language and MATLAB R2007b compiler, for allowing the systematic simulation of a set of water network systems. The application has three main modules (*cf.* **Figure 2**):

- Module 1 – Hydraulic simulator;
- Module 2 – Statistical Analysis;
- Module 3 – Performance Assessment.

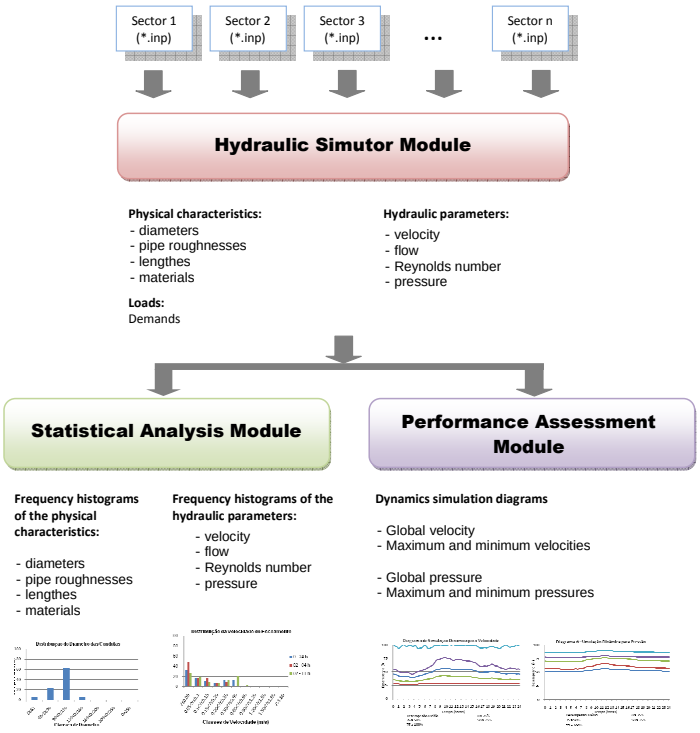


Figure 2 – Diagram of the integrated mathematical model developed using MATLAB

Module 1 (the hydraulic simulator module) allows the simulation of the hydraulic and water quality behaviour of each network system. This module is based in the Epanet Toolkit, which is a set of integrated functions Dynamic Link Library (DLL) that can be used in other applications. The simulator can be used independently of the other modules. For different systems, with different demands and operational conditions, this module determines the hydraulic parameters (e.g., velocity, pressure, head loss, Reynolds number) during a certain period of time. The simulation is carried during 24 hours with a 15 minute time step. Data obtained are saved in a temporary file to be used in the statistical analysis.

Module 2 (the statistical analysis module) carries out the statistical analysis of data obtained in the module 1. This module compiles data and sends it to a MS Excel file. Different classes were considered for each parameter as presented in Table 1.

Module 3 (the performance assessment module) aims at the hydraulic performance assessment of the distribution systems. The performance assessment is carried according the methodology presented by Alegre (1992) and Coelho (1997), and later improved by Jacob (2006) and Sousa (2007). This module is based on the data obtained in the hydraulic simulation module. The variables considered are the maximum, minimum and global velocity and the maximum, minimum and global pressure. Corresponding penalty curves are presented in Figure 3.

Table 1- Hydraulic parameters analysed and classes considered for each parameter

Type	Parameter	Classes
Infrastructure data	Diameter (DN)	]0,63];]63,90];]90,110];]110,160];]160,200];]200,250];]250,500]
	Pipe Roughness (C_{HW})	]0,90];]90,110];]110,130];]130,150]
	Materials	PVC; PEAD; FC; FG
Hydraulic Parameters	Velocity (V)	]0,0.05];]0.05,0.10];]0.10,0.15];]0.15,0.20];]0.20,0.30];]0.30,0.60];]0.60,0.90];]0.90,1.20];]1.20,1.50];]1.50,1.80];]1.80,5.00]
	Head Loss (J)	]0,0.10];]0.10,0.15];]0.15,0.20];]0.20,0.25];]0.25,0.30];]0.30,0.35];]0.35,0.40];]0.40,0.45];]0.45,0.50];]0.50,1.00];]1.00,5.00]
	Reynolds Number (Re)	]0,2E03];]2E03,4E03];]4E03,6E03];]6E03,10E03];]10E03,50E03];]50E03,1E05];]1E05,2E05];]2E05,5E05];]5E05,∞[
	Pressure (P)	]0,10];]10,20];]20,30];]30,40];]40,50];]50,60];]60,70];]70,80];]80,∞[

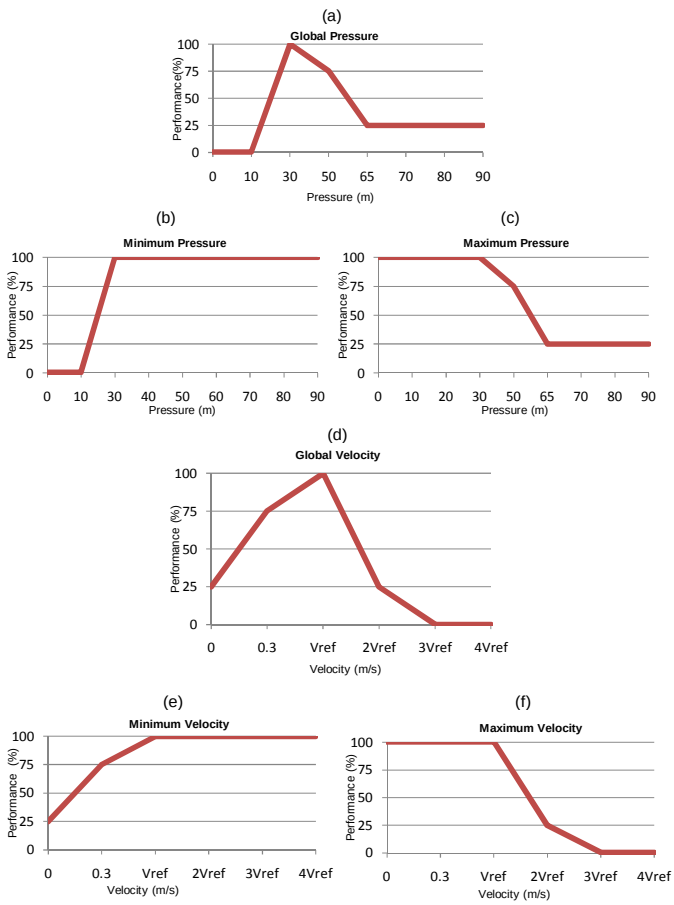


Figure 3 – Penalty Curves: (a) global pressure; (b) minimum pressure; (c) maximum pressure; (d) global velocity; (e) minimum velocity; (f) maximum velocity (Jacob, 2007)

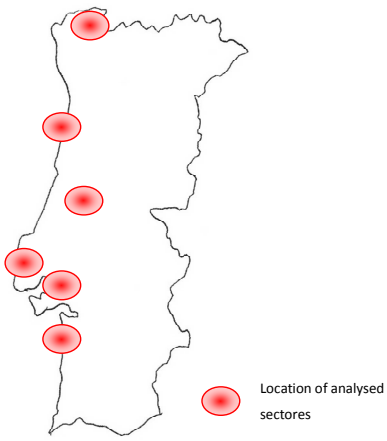
5 SIMULATION AND RESULTS' ANALYSIS

5.1 *Introduction*

The current chapter presents the analysis of the results obtained with the simulation of the 20 systems using the developed software application in Matlab. A global description of the 20 systems studied is presented. Analyses of the physical characteristics and hydraulic parameters are carried out. These analyses are complemented with the performance assessment of the systems for the parameters velocity and pressure. Results obtained are organized in global charts.

5.2 *Study Cases: general description*

The analysis of the systems is carried out during 24 hours and for two periods of the day corresponding to the minimum demand period (i.e., 2-4 hours) and to the maximum demand period (i.e., 7-11 hours). The systems are named from A to T. **Figure 4**(a) presents the spatial distribution of the systems in Portugal and **Figure 4**(b) shows the total length of each system analysed.



Sector	Total Length (m)
A	12 239.7
B	12 623.8
C	21 884.2
D	10 518.1
E	51 380.9
F	19 102.6
G	7 970.8
H	106 862.1
I	45 553.9
J	45 078.9
K	9 329.5
L	15 965.1
M	45 145.2
N	27 705.9
O	21 893.5
P	71 113.1
Q	27 895.5
R	31 125.5
S	12 713.7
T	6 870.3

Figure 4 – Analysed water distribution systems: (a) spatial distribution; (b) total length

5.3 *Analysis of the physical characteristics pipes*

Figure 5 presents the results related to the distribution of diameters per classes for each system and for all systems. The analysis has shown that the major part of the systems have diameters between 63 and 110 mm, except sectors N, Q e T that have predominantly diameters < 63 mm and sector K with diameters in class]110, 160]. Given the small diameters observed, the DMA are belong of pure water distribution networks, whereas sector L presents 30% of its length with diameters between]250, 500] indicating that the presence of water trunk mains in this sector.

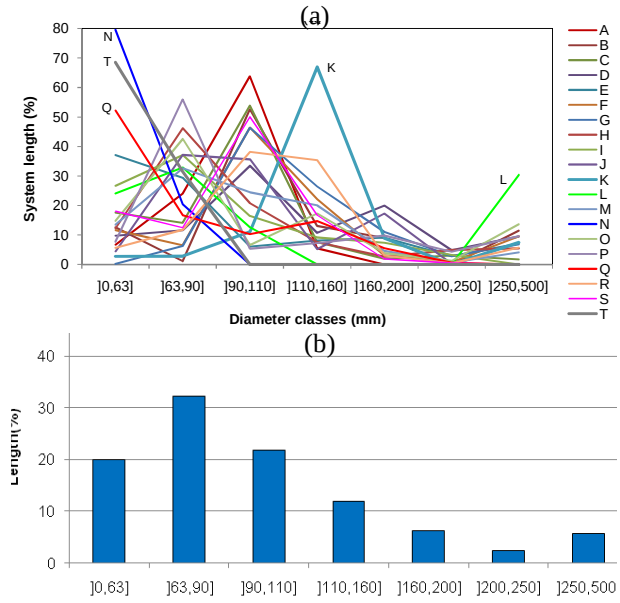


Figure 5 – Distribution of pipe length (a) for each system and (b) for all systems per diameter classes

Figure 6 presents the results related to the distribution of pipe roughness per classes. Analyzing this figure, it is possible to conclude that the major part of the pipes are in the class between]90,110], which correspond to old infrastructures.

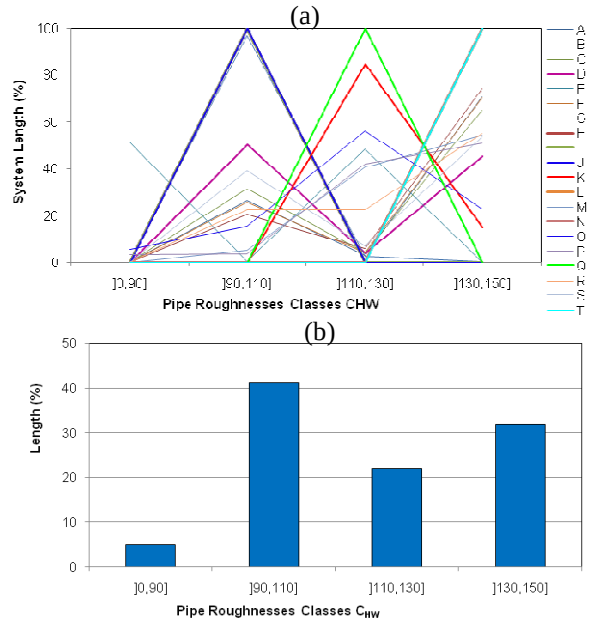


Figure 6 – Distribution of pipe length (a) for each system and (b) for all systems per pipe rough classes

5.4 *Analysis of the technical-hydraulic parameters*

Figure 7 presents the distribution of system lengths per velocity classes. The analysis shows that (i) systems have approximately 60% of their length in the velocity class below 0.05 m/s, and (ii) most systems have, during the day, very low velocities below to the minimum velocity for the peak hour 0,3 m/s (i.e., 90% of the pipes). These low velocities show that the systems are over-sized.

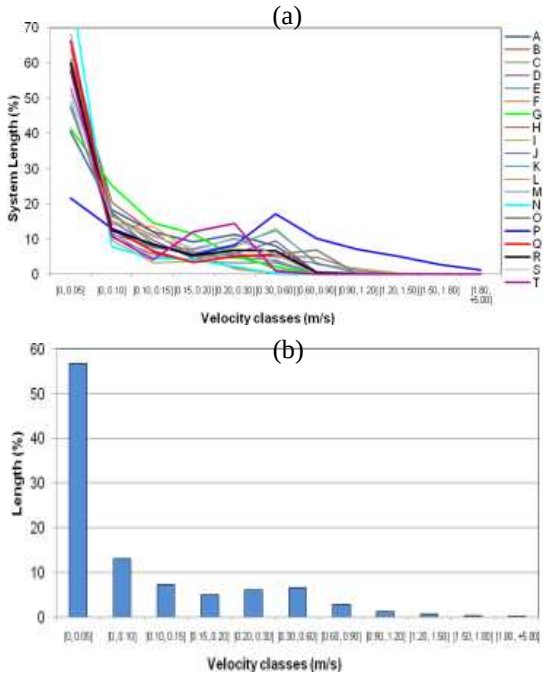


Figure 7 – Distribution of pipe length (a) for each system and (b) for all systems per velocity classes

Figure 8 shows the results for head loss distribution per classes. The head loss distribution is similar to the velocity: 80% of the total length of the systems have head losses below 0,1 m/km. There are some systems (5% of the length) in the highest class]1.00, 5.00] (e.g., systems I, J, O, P, T).

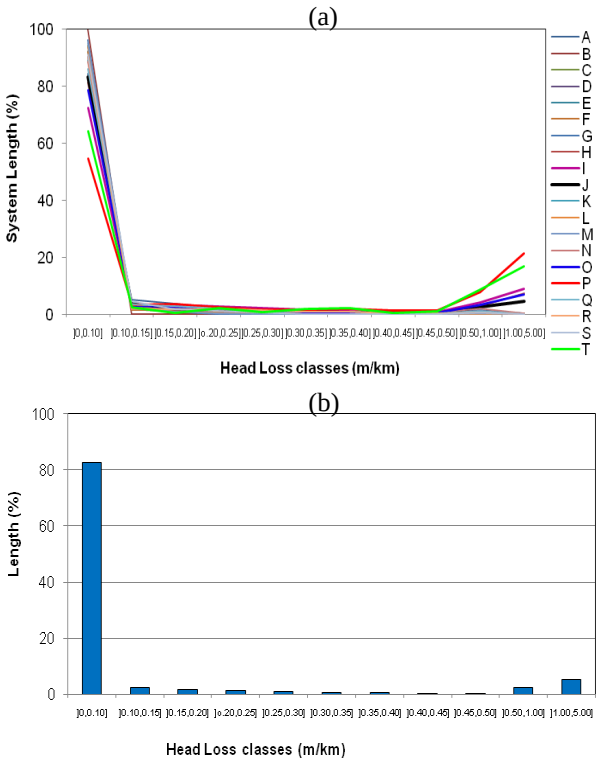


Figure 8 – Distribution of pipe length (a) for each system and (b) for all systems per head loss classes

Figure 9 shows the results related to Reynolds Number distribution. All systems have a significant part of their length, during the day, in the lowest class]0, 2000] followed by the class]10 000, 50 000]. These results are consistent with the low velocities observed; however do not allow concluding about the flow regimes in the pipes due to being the average velocity in every 15 minute, whose instantaneous values can vary significantly, being eventually zero.

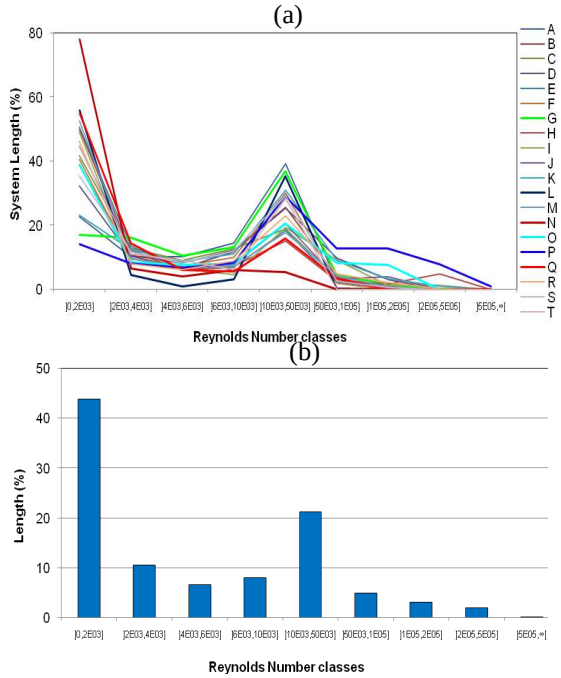


Figure 9 – Distribution of pipe length (a) for each system and (b) for all systems per Reynolds Number

Figure 10 shows the results related with the distribution of pressure per classes. All the systems have a great part of their daily consumption with pressures between 50 and 60 m. Some systems present high pressures what is related with hydraulic problems. There is a significant potential of pressure reduction in the systems with consequent water losses reduction, energy saving and O&M cost reduction.

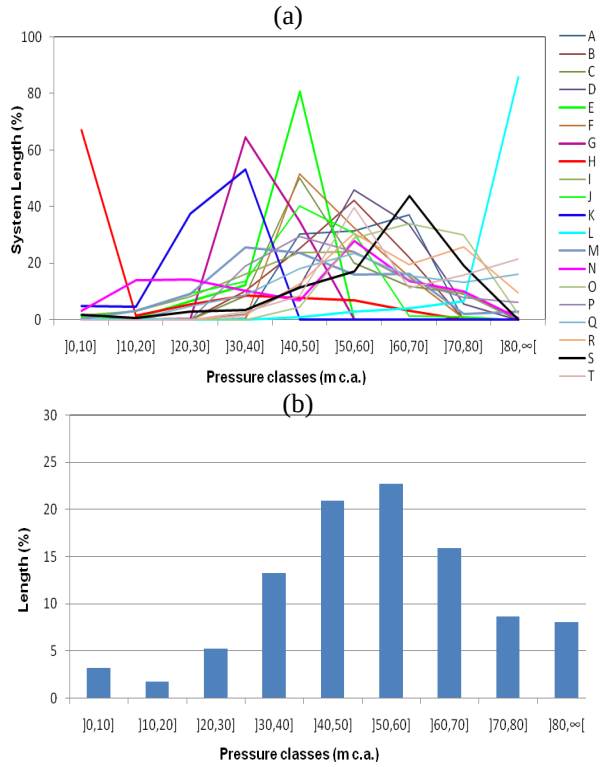


Figure 10 – Distribution of the length (a) of each system and (b) for all systems per pressure classes

5.5 *Performance assessment in terms of velocity*

The following figures show the results obtained for the performance assessment in order to velocity (global, minimum and maximum). **Figure 11** shows the average performance related to the global velocity. All the systems have an average performance between 25 and 75%, except system P with a high performance (70%), system E and N with low performances (i.e., 30 and 40%, respectively) and system H with a performance between 40 and 60%.

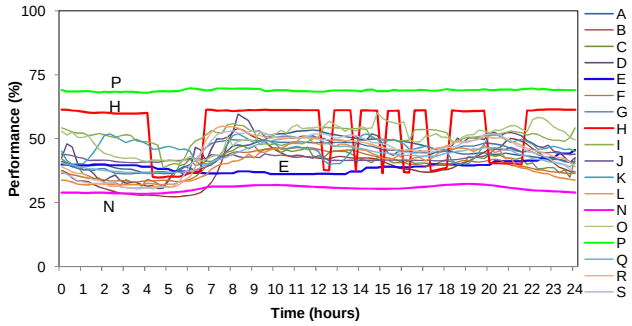
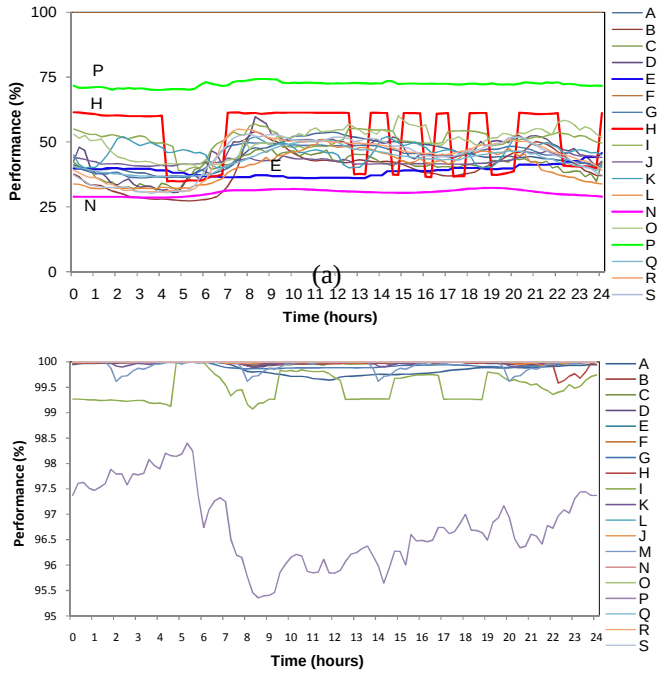


Figure 11 – Performance assessment related with global velocity for all systems

However, performance assessment in terms of the global velocity does not allow for the identification of problems. Thus, this analysis should be complemented with the performance assessment of minimum and maximum velocities, as presented in



(a)

Figure 12. **Average performance curves associated to minimum velocities are similar to those of global velocity, meaning that hydraulic problems associated to velocity are caused by these low velocities**

(

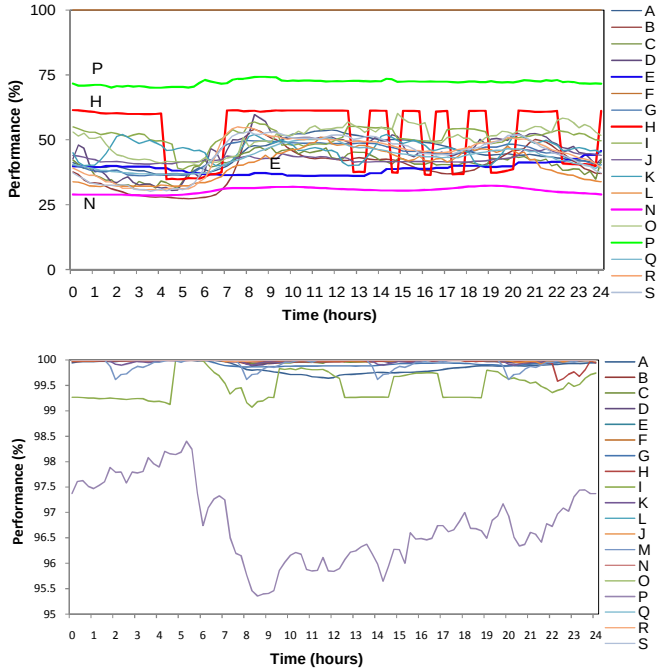


Figure 12**a). Performance assessment related to maximum velocity shows that the systems have performance close to the optimum level**

(

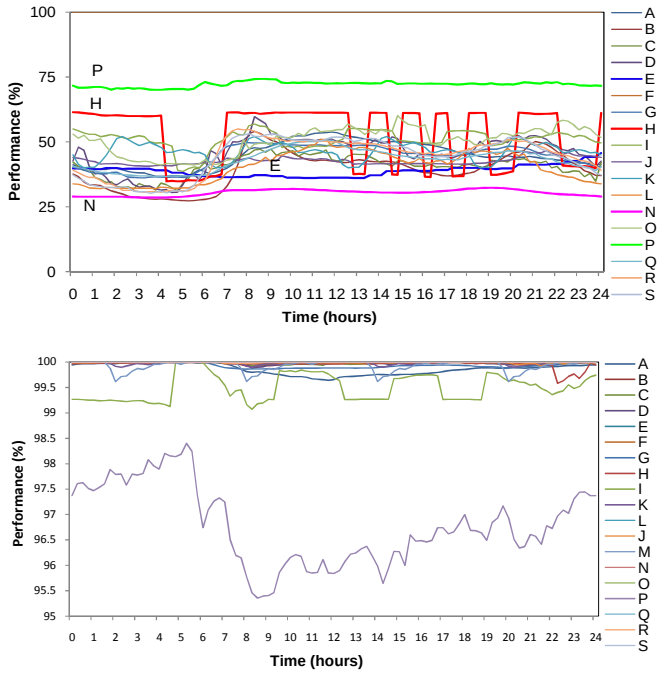
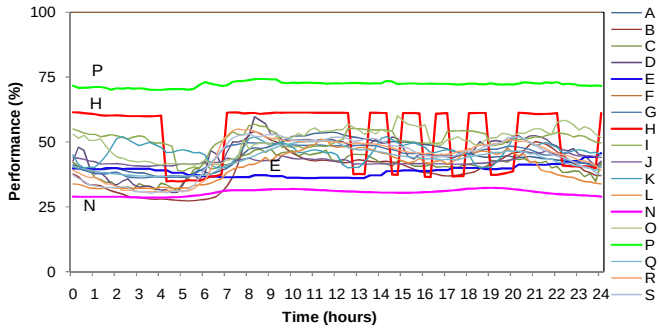


Figure 12b).



(b)

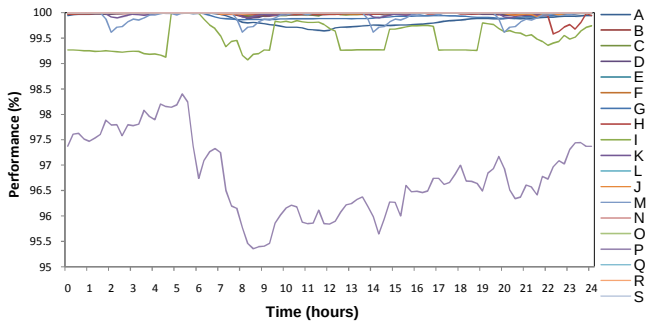


Figure 12 – Performance assessment related to velocity for all systems (a) minimum and (b) maximum

5.6 *Performance Assessment in terms of pressure*

Figure 13 shows the results related with performance assessment in terms of global pressure. The analysis shows that: (i) it is not possible to identify a frame of values, however, most of systems have an average performance curve between 50 and 75%; (ii) some systems have a bad performance (both high and low) which indicates these have hydraulic problems.

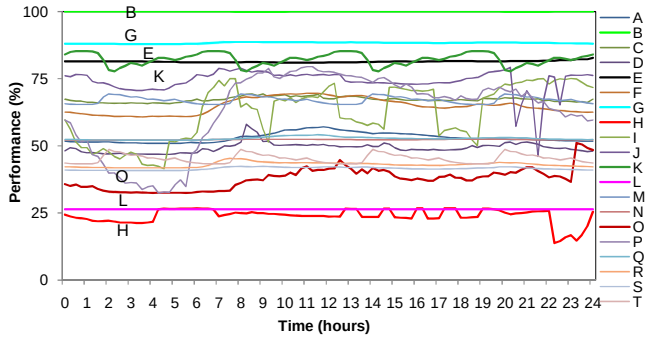
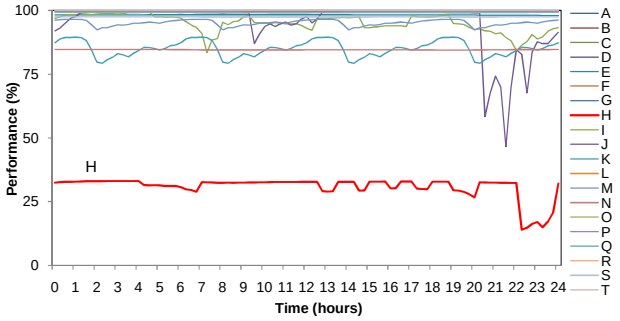


Figure 13 - Performance assessment related with global pressure for all systems

Figure 14a) shows the results related with performance assessment of minimum pressures. Accordingly, all the systems have a performance above 75%, with the exception of system H that has a low performance associated with minimum pressures. **Figure 14**b) presents the results for performance assessment associated with maximum pressures. All the systems have average performance curve above 25%, however it is not possible to identify a frame characteristics values. It is possible to observe that system H, which had a low performance assessment related with minimum pressure, has now a high performance associated with maximum pressure.

(a)



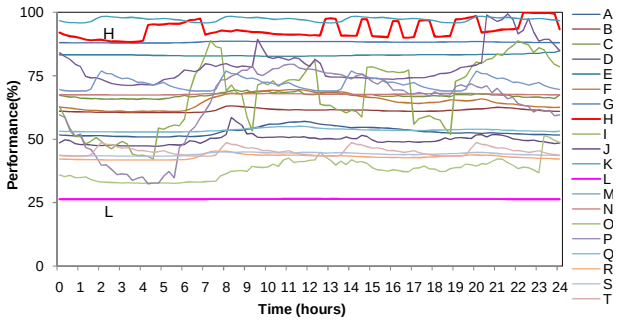


Figure 14 - Performance assessment related with pressure for all systems (a) minimum and (b) maximum

(b)

6 CONCLUSIONS

6.1 *Physical Characteristics of the Infrastructures*

Analysed systems present diameters between]63, 110], which indicates that these correspond to distribution networks (not trunk mains). Concerning to pipe roughness, the systems present a wide range of values: the oldest systems have values between]90, 110] which correspond to old pipes or with high incrustation, whereas other systems have values between]130, 150] that correspond to plastic materials and to asbestos cement with low incrustation.

6.2 *Hydraulic Parameters Analysis*

Network systems have a great part of their length with velocity values below 0,05 m/s during all day. This shows that systems are over-sized for actual consumptions in normal operational conditions, and therefore may have water quality problems.

The head loss distribution is similar to that of velocity: 80% of the total length of the systems have head losses below 0,1 m/km; there are some systems with head losses in the highest class]1.00, 5.00].

All systems have a significant part of their length during the day in the lowest class of Reynolds Number, that is]0, 2000], as well as, in the class]10 000, 50 000]. These results are consistent with those for low velocities, however do not allow to conclude about the flow regimes in the pipes due to being average 15 minute-values, whose instantaneous values can vary significantly, being eventually zero.

All the systems have a great part of their daily consumption with pressures between 50 and 60 m. Some systems have high pressures what is related with hydraulic problems. There is a significant potential of pressure reduction.

6.3 *Performance Assessment*

All the systems have a performance assessment related with global velocity between 25 and 75%. Performance assessment related to minimum velocities is similar to the performance assessment of global velocity what means that hydraulic problems associated with velocity are caused by low velocities. Performance assessment related to maximum velocities shows that all the systems have an average performance near 100%.

Most of the systems have a performance related with global pressure between 50 and 75%. The analysis also shows that some systems have poor assessment (both high and low) what led to conclude that some systems have hydraulic problems. All the systems have a performance assessment (minimum pressure) above 75% exception to system H that has a low performance associated with minimum pressures. All systems have a performance associated with maximum pressure above 25%.

6.4 *Final remarks*

The current research focused on the analysis of the technical hydraulic parameters of a set of district metering areas (managed by Portuguese water utilities). It includes technical performance assessment of the systems. Two main conclusions can be drawn.

First, most systems are over-sized with very low velocities during a substantial part of the time. This is due to the pipe design being carried out for peak load conditions in 40-year time, based on rough estimates of populations and of per capita consumptions, values that most of the times are not attained. Additionally, networks are designed for fire-fighting conditions which correspond to using high minimum diameters.

Secondly, most systems have pressure in excess, being evident the potential of savings of energy and water (losses). This is many times due to the need of supplying consumers at higher elevations.

7 REFERENCES

Alegre, H. (1992) -"Decision support tools for technical management of water distribution systems", PhD Thesis, Vol. 1 of the series «Thesis and Research Programmes», LNEC, Lisbon, Portugal (598 pp., in Portuguese).

Cesario, L. (1995). Modeling, Analysis, and Design of Water Distribution Systems. American Water Works Association, Denver, EUA.

Coelho, S. T. (1997). Performance in Water Distribution – A System Approach, Research Studies Press, Ltd., England.

Grayman, W. M., Clark, R. M., e Males, R. M. (1988). "Modeling distribution-system water quality: dynamic approach." Journal of Water Resources Planning and Management, ASCE, 125(2), 295-311.

Jacob, A. (2006). "Assessment of water loss in water distribution systems: the study case of ZMC 320 EPAL" Master Thesis in Hydraulic and Water Resources, Instituto Superior Técnico, Universidade Técnica de Lisboa, Portugal.

Mays, L. W. (2000). Water Distribution Systems Handbook. McGraw-Hill, EUA.

Sousa, C. (2007). "Multiobjective Optimization of Water Supply Systems Operation Using Genetic Algorithms." Master of Science Thesis in Hydraulics and Water Resources, Instituto Superior Técnico, Technical University of Lisbon, Portugal.

Vidigal, P. M. (2008). "Extended Analysis of Technical-Hydraulic Parameters and Performance Assessment in Water Distribution Systems". Master of Science Thesis in Civil Engineering, Instituto Superior Técnico, Universidade Técnica de Lisboa, Portugal (in Portuguese).

Walski, T. M., Chase, D. V., Savic, D. A. (2003). Advanced Water Distribution Modeling. Haestad Methods Press, EUA (www.haestad.com).