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MODELLING HIGH PRESSURE FLOW AND REPLACEMENT OF PIPES IN WATER SUPPLY SYSTEMS IN NORTH PORTUGAL*

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Abstract– Public water supply networks in Portugal do not have, in general terms, management and monitoring systems, either at the level of quality or at the level functioning of the hydraulic system itself (pressures, speeds, water leaks and losses, among others). In order for any management system to function, it is obviously necessary that its physical features are known, which does not occur in most cases. For instance, the record of the supply networks and branch-lines of connection to consumers are unknown, and the same occurs regarding the features of the material used (type of material, diameters, accessories, among others), that is, it completely derails the implementation of any software that may be able to help the managing entities of these water supply systems that are mostly Municipalities or, at times, concessionary companies.

The study presented hereafter was carried out in two cities in North Portugal and intends to demonstrate the usefulness of an effective system that has the potential to manage water supply networks. In both cities, target areas of this study were delimited (each one with over 6 000 inhabitants, this being one of the assumptions of the software used). Another particularity is that in the city of Vila Real, the water supply system is managed by the Municipality, whereas in the city of Fafe, it is managed by a concessionary company, "Indaqua". After the sub-systems were physically designed, the simulations that proved more beneficial were the ones that consider Pressure Reducing Valves (PRV's), as North Portugal is rather rough in topographical terms, which causes exaggerated pressures on the pipes, frequently exceeding the limit allowed by the Portuguese Law (600 KPa). Among other simulations that have been performed, this was, in fact, the one that clearly and objectively allowed engineers to know where the location should be or locations to place these PRV's in the sub-systems of both cities. The replacement of pipe sections was also one of this work's approaches, since it is urgent to deactivate many pipes that are degraded and obstructed. With the simulations performed, it will be possible to analyse which is the system's hydraulic behaviour and which will be the impact (social, for instance) of the deactivation of some sections.

Keywords– Monitoring, management, pressure, Epanet, GIS

1. INTRODUCTION

The Water Framework Directive [1] established a community action framework for surface and underground waters and set new and audacious challenges towards improving water resources' problems. A public supply system has the fundamental goal of providing enough water, in quantity and pressure terms, of a good quality and without interruptions. However, and for many years in Portugal, efforts have been concentrated only in building new supply infrastructures, while the management and monitoring

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were somehow overshadowed. Moreover, it is important to consider the increase in confidence and safety regarding the services rendered, due to the use of computational tools that help decision making, thus supporting the solution of complex planning problems.

Tundisi *et al.* [2] have listed a number of problems concerning the social, economical and environmental contexts of the 21^{st} century related to water resources and their management, that is, to the "water crisis". The need for a systemic, integrated and predictive approach in waters management is increasingly more evident and critical [3], thus reflecting an economic assessment of the services of the water resources and ecosystems [4]. According to the Strategic Plan for Water Supply and Sewerage Services 2000-2006 [5], in Portugal one of the vital objectives is the increase in the level of service to population with home water supply (around 95%), and the improvement of its quality for consumption. Notwithstanding the considerable progress already achieved, unsolved critical issues in the water sector still prevail, which are a clear challenge strategy with action lines within the scope of the environmental requalification, integrated solutions, high service quality and above all, guarantee of sustainability for the programming period 2007-2013.

Presently, in most developed countries, the main flaws detected in water supply systems are due especially to the deterioration of the older systems, namely in the part of the water supply in which pipes are fractured and cause water leaks, that is, the lack of a good supply in terms of quantity, quality and pressure [6].

In a water supply system, the fight for the reduction in leaks and losses is the most relevant activity when the improvement of this system's efficacy is intended, leading to the creation of mechanisms to quantify and qualify the systems using operational instruments such as models of simulation of supply networks. The simulation models aim at predicting the system's response in face of wide ranges of operational and environmental conditions, without the need to intervene with the system itself or to endanger it with unknown operation modes [7-9]. Problems may be anticipated and the solutions may be assessed before making investments [10] by using telemetry systems, as they function with a highly automated technique of communications with the support of measurements and data organization made in remote locations and subsequently sent for real time monitoring [11].

There are several classifications and formulations of the simulation models, namely according to the variable time, to their use and to their goal [12]. Among other models of hydraulic simulation of pressurized systems of water supply networks, the EPANET model [13, 14] stands out. This model provides, for a given period of time, the values of the pressure on the knots, levels of water in the reservoirs, cost of pumping energy, and the parameters of the water quality in the whole supply network. This model is also highlighted for being a program of public domain and for the fact that its quality has been reinforced in many studies. It is one of the most used models for hydraulic simulation in many countries. One example is that of the sector of water supply in the neighbourhood of Nossa Senhora de Lourdes and its outskirts in the city of Santa Maria, Rio Grande do Sul, Brazil [7]. With the modelling made and the practical results of the simulation found, it was possible to diagnose two situations in which the program generated improvements' projects, the first being the identification of areas with high pressure and the subsequent project that allowed the installation of PRV's in the main points. The second one consisted of the selection of sections of the supply network where the charge losses were high, caused by high pressures, leading to lack of regularity in the supply in certain sections. Aimed at solving this problem, the simulation allowed the acknowledgement and the dimensioning of the pipes needed for the operational improvements. Also, in the State of Virginia (supply network of Koppie Allen, Balkfontein), United States of America, EPANET was used within the scope of the assessment of the water quality parameters in the whole supply network. The disinfection of the water after being processed is a critical and necessary condition before it may be supplied to consumers. The simulation model determined the retention times, the age of the water in any given point, as well as the concentrations of chemical substances and the indicated quantity for the supply network, reducing in 99.9% of the infectious chemical substances [15]. Likewise, in Iran, as a complement or support to the determination of leaks and losses using another method, the EPANET model was used [9]. Another example of the application of this popular model in the management and modelling of pressures was the city of Mutare, in Zimbabwe. Furthermore, the application of this model to control leaks and losses in parts of the city was recommended in this study [16]. Araújo *et al.* [8] have used this hydraulic model, associated with genetic algorithms, to make an optimized and integrated pressures management, making, at the same time, the optimization and location of valves.

Concerning the use of EPANET in Portugal, notwithstanding being incited by the National Laboratory of Civil Engineering, few applications have been made in this country. However, two are presented hereafter, the first being implemented by the company Águas do Vouga in the Regional System of Carvoeiro (RSC), and the second by the Municipal Services of Water and Sewage (Serviços Municipalizados de Águas e Saneamento - SMAS) of Porto. RSC is a high pressure water supply system, at the regional scale, which supplies water to the counties of Águeda, Albergaria-a-Velha, Aveiro, Estarreja, Ílhavo, Murtosa and Ovar, in a region of 270 000 inhabitants [17]. The implementation of this simulation model had the objective of being an instrument to support the definition of operation and exploration strategies (that is, opening and closing of control valves, pumping schedules, identification of the locations in need of maintenance and/or possible expansion, among others), included in a process of optimization of transport and processing of water captured in the area of the Carvoeiro (river Vouga). Regarding the application of the model by Porto's SMAS, it was used in a pilot area, corresponding to approximately 65 km of ducts which supply nearly 10 350 inhabitants [10].

There were three main purposes to applying this management and monitoring system of water supply network (EPANET 2.0) to two cities in North Portugal. The first has to do with favouring the work activities (planning, project, exploration and maintenance) and with highlighting the relevance of the management and monitoring of the supply network of Cumieira to the Managing Entity INDAQUA – Indústria e Gestão de Águas, SA – Fafe and EMAR in Vila Real. The second goal was to apply and assess the use of the hydraulic modelling software, the EPANET, in the Supply System of both these cities. The third and last purpose was to expand the charts to present the several hydraulic parameters of the supply systems, promoting and encouraging the use of these tools, as there was visible satisfaction on the part of the managing entities from these cities in North Portugal when they realized in reality (with objective data from the ground) the kind of advantages that the tools could provide them, especially in simulations such as the introduction of PRV's (associated to charts of pressures and speeds' visualization, among others), replacement of pipes or any other kind of designed scenarios.

It should be mentioned that the version used is a model of simulation of public water supply developed by the United States Environmental Protection Agency (USEPA), in the United States of America, that distributes it free of charge along with several support materials, and which has been adapted to the Portuguese language by the National Laboratory of Civil Engineering.

2. MATERIALS AND METHODS

a) Description and justification of the locations studied

This study was carried out in Fafe and Vila Real, two different cities in North Portugal (Fig. 1). Fafe, with a population of 53 000 inhabitants, has an average elevation of 350 meters, a climate rated as mild and wet and a relative humidity varying from 70 to 85%, whereas Vila Real has a population of nearly 30 000 inhabitants and has an average elevation of 450 meters. In terms of climate, this city possesses a climate of extremes. On the one hand, it has a fairly long winter, the cold being constant, frequently reaching temperatures below 0 ºC, and it is usual to snow at least once a year. On the other hand, it has a rather warm summer, with temperatures around 40 ºC. The intermediate days are rare, the differences in temperatures being very abrupt [18, 19].

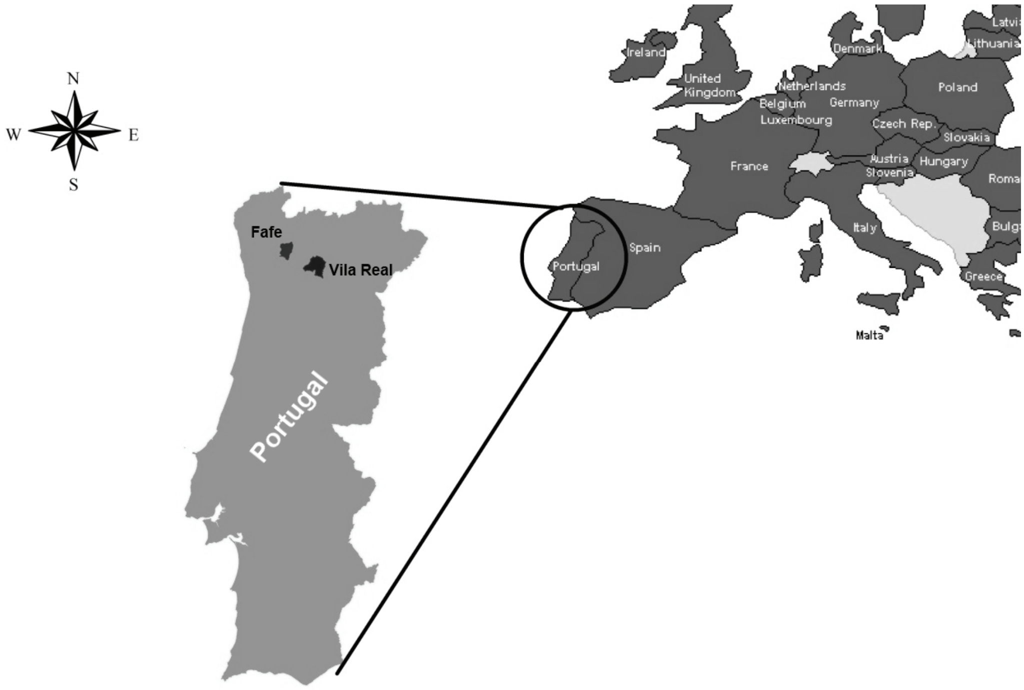

Fig. 1. Location of the counties of the cities under study

In both cities three possible simulation scenarios were created: the repair of a damaged pipe; the replacement of a pipe by another of a bigger diameter and the installation of a PRV, taking, thus, some abilities of the simulation model in planning the maintenance activities and work operations, and the ability of the model to respond and present alternatives to possible occurring situations was, in fact, acknowledged. The example of too much pressure in the supply networks of both these cities is a fact, due mainly to the ground's orography, hence justifying the planning concerning the PRV's placement.

b) Description of the model

The construction of the system was mainly composed of the collection of data needed for its physical description, that is, we collected the record of the network (diameter, material, accessories, among others), reservoirs (type, capacity, and piezometric height), ducts, valves and other physical elements.

In modelling the systems under study, a Geographical Information System (GIS) was designed. To do so, the ArcView GIS 3.3 software was used, and, hence, the whole record of the network was registered in a computer file, containing a complete physical description of the georeferenced systems. In fact, the availability of the network's record in a GIS allows the manipulation of input and output data. Therefore, the model was created in a*.inp* format file that subsequently was exported to the EPANET 2.0 software, aimed at performing the hydraulic simulation of the supply systems under study.

A structural scheme is presented hereafter (Fig. 2), in order for us to have an overall perception of the work carried out and to understand the normal path from data input to the simulation of the designed or anticipated scenarios.

Consumption determination requires special care, since it is the major source of uncertainty associated with the model. This represents the water consumption of several user groups, that is, domestic, industrial, watering, losses, among others. Consumption distribution in the network was made by the ducts through the supply branch-lines. However, in the simulation models, in general and by simplification, consumptions are attributed as being applied in the knots that delimitate the ducts [20]. Therefore, there are several ways to determine a network's consumptions, based on the cartographic analysis, on billing data, on the interconnection GIS – billing system – model, among others. In this work, the domestic use being the major one, the consumptions' attribution has been made through the Coefficients of Use (CU) method. This method consists, basically, of attributing consumptions according to the density of users regarding each duct on the ducts' nearby knots.

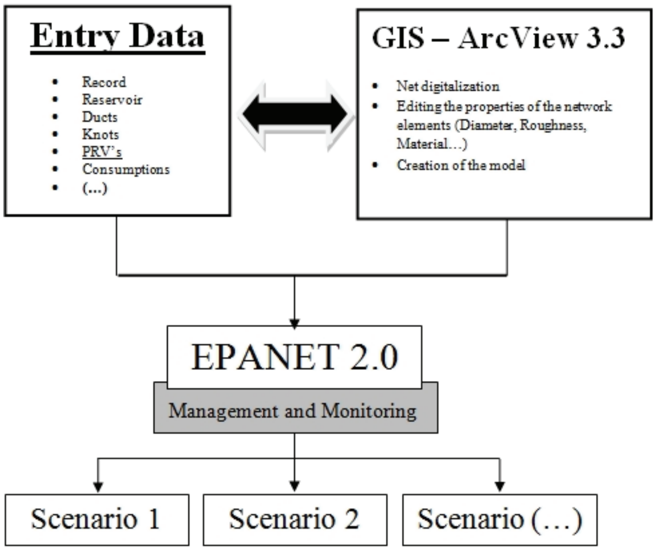

Fig. 2. Structural scheme of the work carried out

CU was determined through the quotient between the number of counters supplied by each pipe and the maximum number that a pipe can supply, resulting in the following equation:

$$CU_i = \frac{NC_i}{NC^{\max}}$$

Where:
CU_i – coefficient of use of the pipe i;
NC_i – number of Counters that pipe i supplies;
NC^{max} – maximum number of counters that a pipe supplies.

Being the pondered length, the result of the product between the coefficient of use and the length of the pipe i, resulting in the following equation:

$$L_i^{pond} = CU_i \times L_i$$

Where:
L_i^{pond} – pondered length of pipe i;
L_i – length of pipe i.

The pipes' total pondered length comes from the sum of the pondered lengths of all pipes, resulting in the following equation:

$$L_{Total}^{pond} = \sum_{i=0}^{n} L_i^{pond}$$

Where:
$L_{Total}{}^{pond}$ – total pondered length of all pipes;
N – number of pipes existing in the network.

In the third and last stage of consumptions' determination, the consumptions of each knot j of the network are obtained through the following equation:

$$C_j = \left(\frac{\sum_{i=1}^{n} L_i^{pond}}{2} \times \frac{1}{L_{Total}^{pond}} \right) \times Q_D + Q_j{}^{GC}$$

Being:
C_j – consumption of knot j;
$L_{Total}{}^{pond}$ – total pondered length of all pipes;
$L_i{}^{pond}$ – pondered length of pipes i confluent in knot j;
N – number of pipes i confluent in knot j;
Q_D– consumption of the network without big consumers;
$Q_j{}^{GC}$ – consumption of the big consumer concentrated in knot j.

3. RESULTS AND DISCUSSION

a) Scenario 1 – Pipes repair

It may be understood by the scheme illustrated in Fig. 3, the knots and pipes were directly influenced by the repair of pipe AD in a duct in Fafe. It may be observed that there is a change in the direction of the pipes' (CD and ED) outflow, in order to somehow satisfy the consumption in knot D.

Similarly, and in the city of Vila Real, Fig. 4 presents the changes caused by the replacement of a pipe; the sections in which the outflow direction has been changed are marked with a circle.

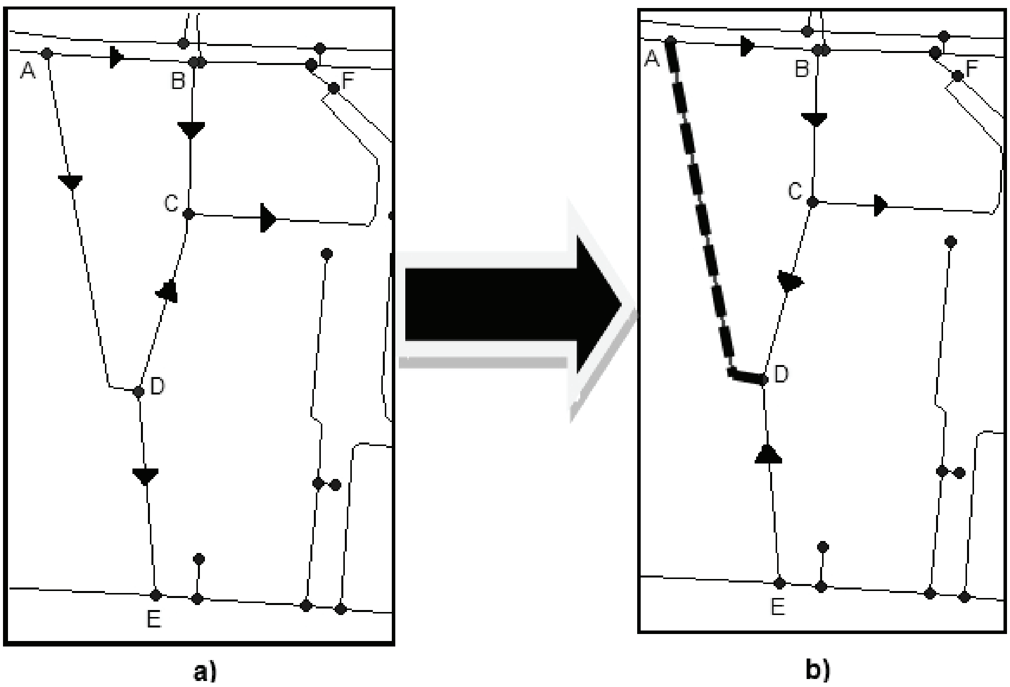

Fig. 3. Scheme of pipes and knots that are directly influenced by the repair of pipe AD in a duct in Fafe – a) open; b) closed

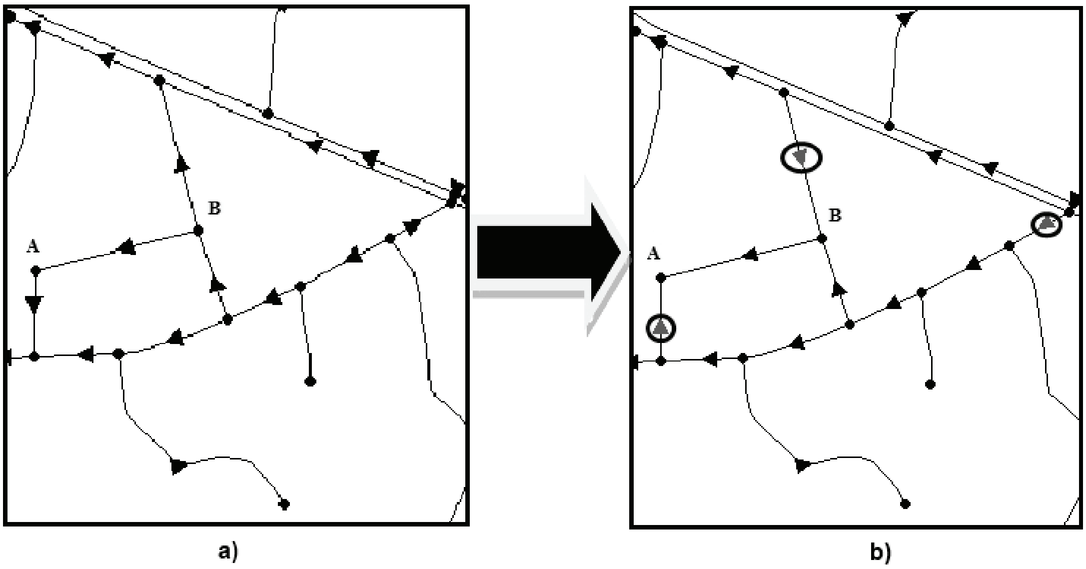

Fig. 4. Scheme of pipes and knots which are directly influenced by the repair of pipes AD – a) open; b) closed

b) Scenario 2 – Pipes replacement

In the second scenario, and regarding the city of Fafe, the effect of a recent expansion in the commercial area was considered, namely the location of new hypermarkets. Such effect caused an increase in consumption and, hence, an increase in the pipe's diameter. Table 1 presents the features of the existing pipes and the replaced pipes.

Table 1. Features of each pipe (Fafe)

	Diameter (mm)	Consumption (l/s)	
		Starting knot	Ending knot
Existing pipes	110	0.08	0.16
Replaced pipes	160	0.30	0.20

Based on this assumption, it has been verified that there was no change in the outflow direction, but rather a redistribution of the flows by the pipes that were directly influenced by the replaced pipes. This change contributes to the reduction of the pressures in each knot, as a result of the increase in the pipe flows and diameters.

The execution of the second scenario for Vila Real aims at simulating the changes to perform on the network in the event that new buildings are raised in Dona Maria de Lurdes Amaral Street, in the parish of Abambres. The increase in the number of buildings will cause an increase in consumption, hence, an increase in the flow carried by the pipes being necessary to increase their diameter. In Fig. 5, the pipes that will supply the new buildings are identified, section A-B.

The existing pipes A-B have features which are different from the replacement pipes. These changes may be observed in Table 2, as well as the changes in the knots next to the pipes.

In Figs. 6 and 7 the pressures in the knots, in black, are presented as well as the flows in the sections in gray, respectively before and after the replacement.

As can be observed, the replacement of the pipes by others with a higher diameter and the consequent increase in consumption has caused a small increase in the flow and a decrease in the pressure, this one remaining within the control values.

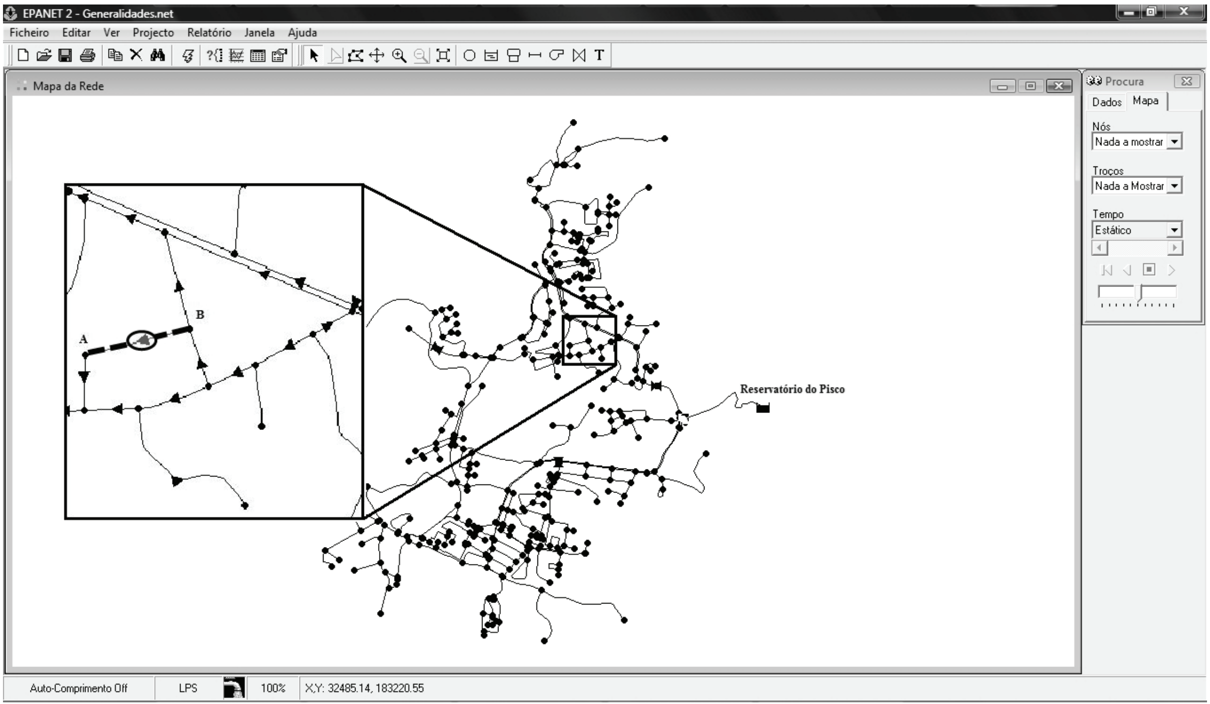

Fig. 5. Identification of the location and pipes to be replaced (Vila Real)

Table 2. Features of each of the pipes (Vila Real)

Section A-B	Material	Nominal Diameter (mm)	Absolute roughness (mm)	Consumption (l/s)	
				Knot 2	Knot 1
Existing duct	PVC	90	0.02	0.007	0.000
Final duct	PVC	125	0.02	0.207	0.200

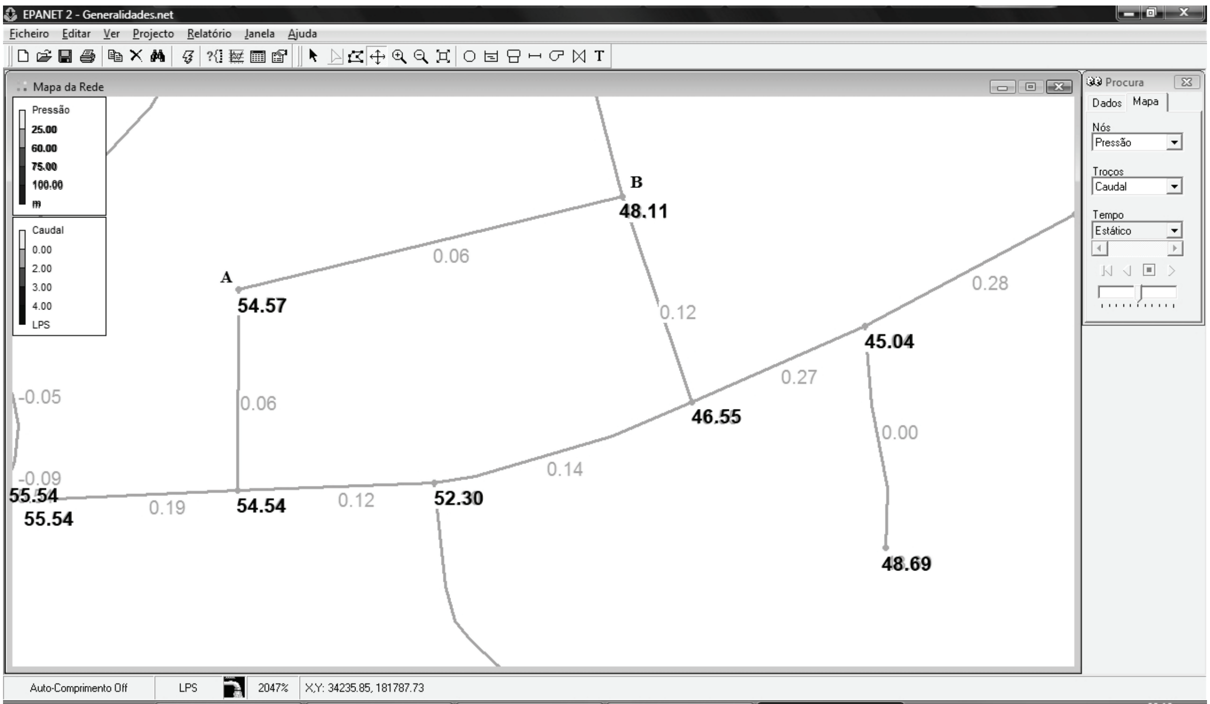

Fig. 6. Pressure in the knots and Flow on the sections before and after the replacement of the pipes (Vila Real)

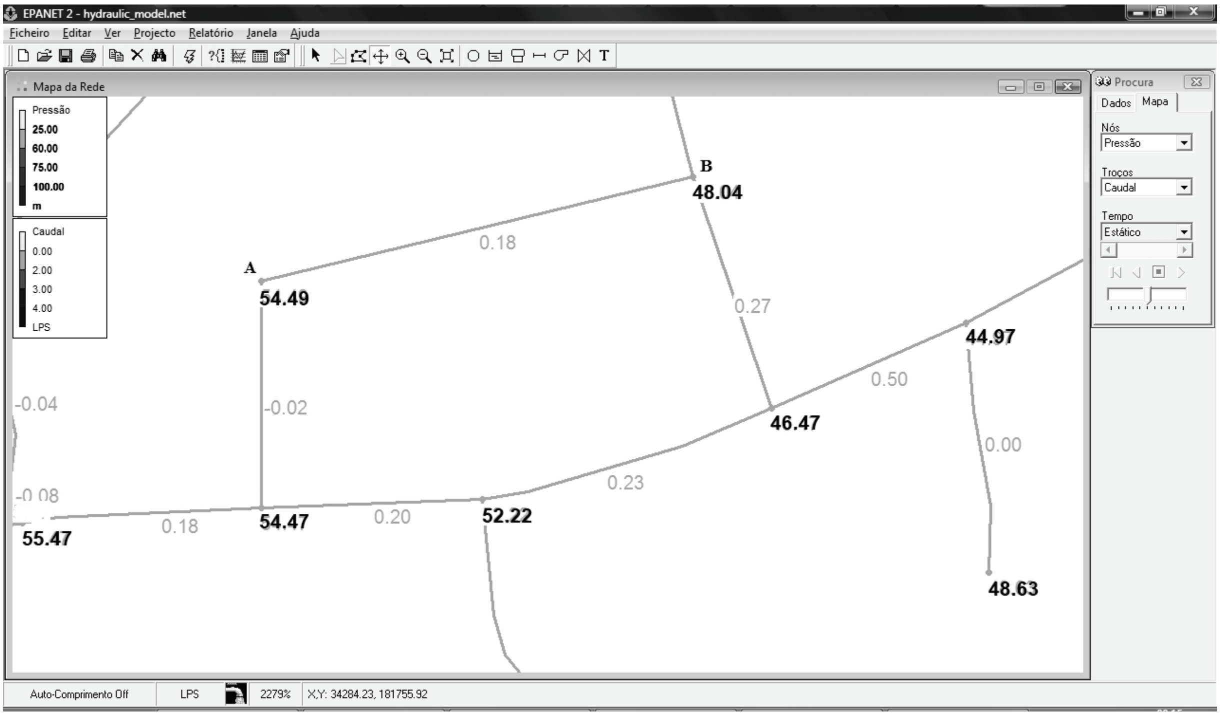

Fig. 7. Pressure in the knots and Flow on the sections after replacement of the pipes (Vila Real)

c) Scenario 3 – PRV's placement

Finally, the third scenario consisted of the installation of PRV's in order to reduce the pressure downstream of a pre-fixed value (Fig. 8), which respects the established in the present Portuguese law [21], which compels pressures in the network lower than 600 KPa.

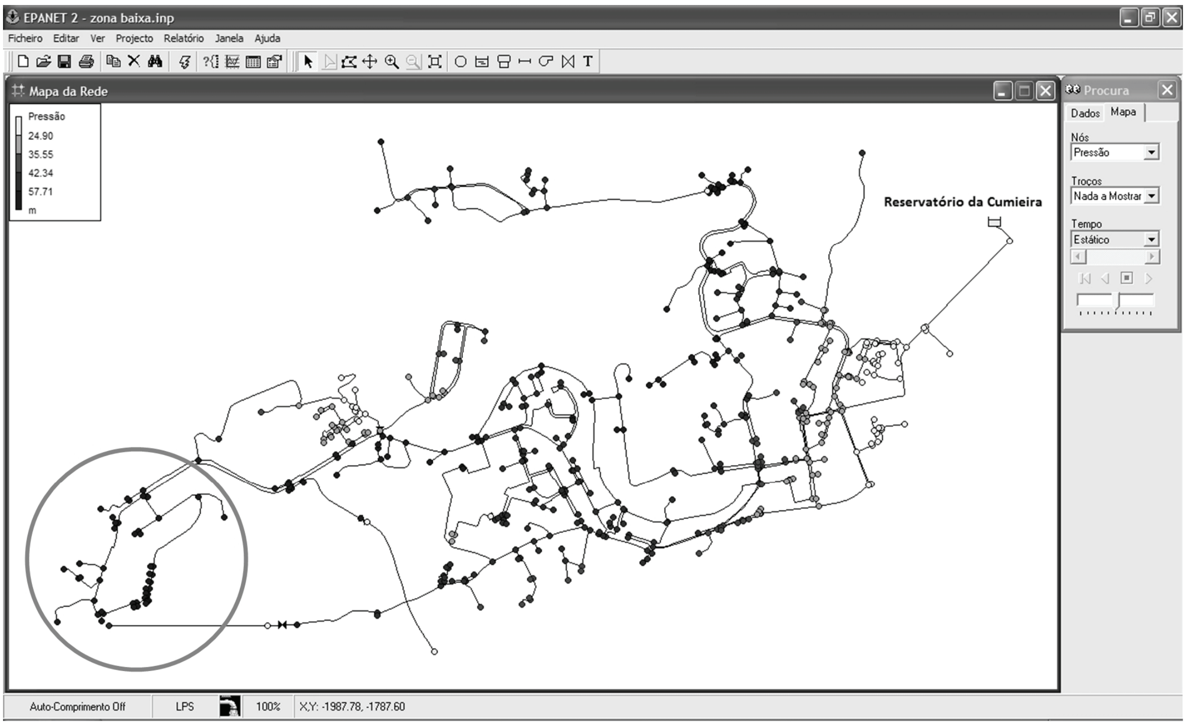

Fig. 8. Location of the region with high pressures, selected in the circle (Fafe)

The installed PRV has similar features to the PRV's already existing on the network. Under these circumstances, it may be observed in Fig. 9 that, after the installation of the PRV, when compared to Fig. 8, a significant improvement in the pressure values in the demarked region can be seen.

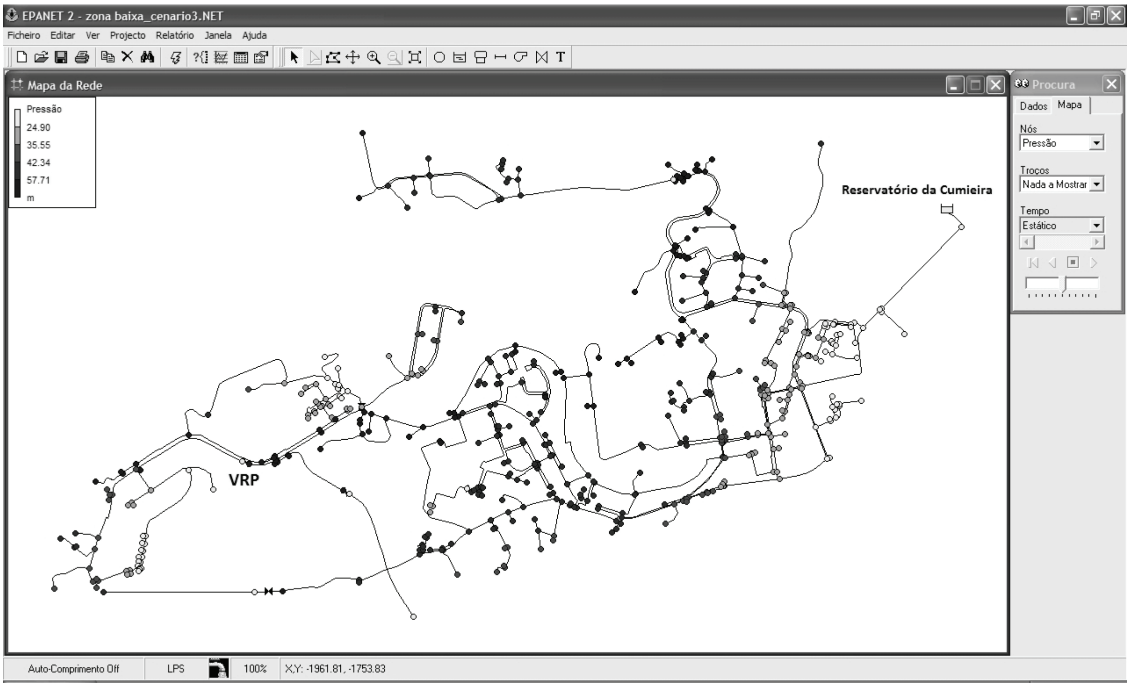

Fig. 9. Location of the PRV's installation on the network (Fafe)

In Fig. 9, the change in the knots' colour is clear (more orange), which consubstantiates lower pressures, around 350 Kpa, which are statutory. By proposing this change, the supply system of Cumieira (low area) becomes more balanced and homogeneous, thus creating an alternative to high pressures.

The execution of this scenario allowed a critical analysis of the quality of the existing operational data, and a need for changes towards the improvement of the functioning of the supply systems as a whole has been noted.

In turn, the Vila Real system's managing entity, EMARVR, is aware of the high record of pressures that the network presents. The causes for such a record are due, above all, to the existing high topographic unlevelling. Therefore, in order to reduce the pressures on the network, the installation of two PRV's in the locations signaled in Fig. 10 is proposed, as well as the reduction in the output pressure of the PRV in Bairro do Marão.

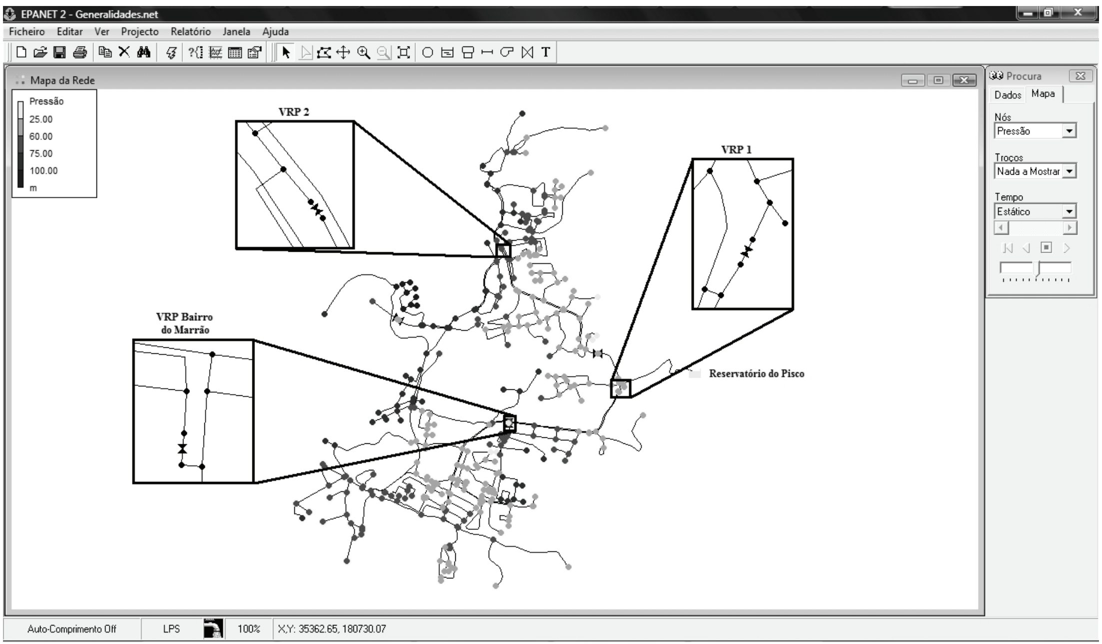

Fig. 10. Location of the PRV's and pressure on the network before their installation (Vila Real)

The installed PRV's are of the same kind and with similar features to the ones already installed on the system of Pisco, as Table 3 illustrates.

Table 3. Features of the installed PRV's, PRV 1 and 2 (Vila Real)

PRV's	Diameter of the duct (mm)		Diameter (mm)	Pressure (KPa)	
	Upstream	Downstream		Upstream	Downstream
PRV 1	125	125	110	674.4	300.0
PRV 2	315	315	250	441.2	200.0

As may be observed in Table 3, the loss of located charge caused by PRV 1 and 2 is, respectively, 374.4 KPa e 241.2 KPa. In the PRV in Bairro do Marão, a change of the valve's output pressure was made by decreasing it. In Table 4 the features of the PRV in Bairro do Marão may be observed, as well as the changes performed in that PRV.

Table 4. Features of the PRV in Bairro do Marão before and after the changes (Vila Real)

PRV's		Diameter of the duct (mm)		Diameter (mm)	Pressure (KPa)		Status
		Upstream	Downstream		Upstream	Downstream	
Before	B. do Marrão	160	160	125	686.2	200.0	Active
After	B. do Marrão	160	160	125	441.4	100.0	Active

In this Table, the pressure upstream of the PRV in Bairro do Marão before and after the installation of two PRVs is evidenced, as well as the change made in the predefined pressure downstream the PRV. It is also possible to deduct the differences related to the loss of charge induced by the mentioned PRV, that is, the loss of charge decreases from 486.2 KPa to 241.4 KPa.

4. CONCLUSION

The designed models offer us a useful tool to provide an effective management and monitoring in the studied systems. GIS was used to provide a georeferenced spatial vision of the studied area and to have a quick recovery through the manipulation of the input and output parameters in the model. It was used to test the conditions of operationality of planning and maintenance of all tasks to be executed on the studied subsystems. We may, therefore, state that the simulation model is also an important decision making support instrument.

The usefulness in applying this tool (EPANET/GIS) was very profitable for the managing entities of both these cities in North Portugal, mainly because it has allowed to simulate the reduction of pressures on the network, which permanently endanger the supply system itself, but also to show and simulate the hydraulic behaviour in face of interventions in pipe sections that daily affect thousands of people all over the country. It will also be appropriate to implement, using the same software, studies on the quality of the water along the sections, as well as the application of submetric sensors that would help detecting leaks and losses on the systems, which frequently are over 60% of the input water in the network (after capture and processing).

At the moment, and as far as the city of Vila Real, capital of the Northeast, is concerned, we are georeferencing the whole network (up to the user/consumer) in order to be able to associate the inhabitant/consumer to the network or to its access branch-line (both in the individual and in the collective case). The implementation of this system, associated with the management and monitoring of the whole supply network, will be a gain for the city, and we are hopeful that other managing entities shall follow the same path.

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