UNIVERSITAT POLITÈCNICA DE VALÈNCIA

ESCUELA TÉCNICA SUPERIOR INGENIEROS INDUSTRIALES VALENCIA

TRABAJO FIN DE MASTER EN INGENIERÍA INDUSTRIAL

COMPARATIVE STUDY OF THE ENERGY EFFICIENCY IN PRESSURIZED WATER TRANSPORT SYSTEMS

AUTHOR: MARIANO AGUDO BLANCO

SUPERVISOR: ELENA GÓMEZ SELLÉS

Academic year: 2016-17

RESUMEN

El presente Trabajo Final de Máster pretende ilustrar la creciente necesidad en la actualidad de la mejora de la eficiencia energética en sistemas de transporte de agua a presión. Para ello es necesario tanto el estudio de la red en cuestión como la comprensión de ésta en profundidad.

Con tal fin, el trabajo mostrará una metodología de análisis energético de redes de agua a presión en la que se podrán examinar los diferentes aspectos técnicos que tienen una repercusión directa o indirecta en la eficiencia energética. Se trata de una metodología reciente desarrollada por Aguas de Valencia en colaboración con la UPV cuya meta es ser implantada en la operación diaria de la compañía.

Además, se ilustrará el proceso con la ayuda de dos casos prácticos de redes de agua: Teruel y Sagunto. Se trata de abastecimientos con diferentes características y configuraciones que permitirán el análisis desde diferentes enfoques y que darán validez a la metodología desde un punto de vista práctico.

El trabajo comenzará con un análisis de las redes de agua a través de herramientas informáticas como Epanet o ITAEnergy entre otras, que facilitarán el proceso de evaluación de las redes.

Los resultados del trabajo proporcionarán medidas de ahorro que supondrán una mejora en la eficiencia energética del sistema con la meta de poder utilizar los procedimientos aquí descritos en todo tipo de abastecimiento de agua presión.

Palabras clave: Red de agua a presión, eficiencia energética, metodología de mejora energética, medidas de mejora energética, válvula reductora de presión (VRP), sectorización, ahorro de agua, ahorro energético.

RESUM

El present Treball de Final de Màster pretén il·lustrar la creixent necessitat en l'actualitat de la millora de l'eficiència energètica en sistemes d'aigua a pressió. Per aconseguir-ho es necessari tant l'estudi de la xarxa en qüestió com la comprensió d'esta en profunditat.

Amb esta finalitat, el treball mostrarà una metodologia d'anàlisi energètic de xarxes d'aigua a pressió on es podran examinar els diferents aspectes tècnics que tenen repercussió directa o indirecta en l'eficiència energètica. Es tracta d'una metodologia recent desenvolupada per Aguas de Valencia en col·laboració amb la UPV, la meta de la qual es ser implantada en l'operació diària de la companyia.

A més, s'il·lustrarà el procés amb l'ajuda de dos casos pràctics de xarxes d'aigua: Teruel i Sagunt. Es tracta d'abastiments amb diferents característiques i configuracions que permetran l'anàlisi des de diferents enfocaments i que donaran validesa a la metodologia des d'un punt de vista pràctic.

El treball començarà amb l'anàlisi de les xarxes d'aigua utilitzant ferramentes informàtiques com Epanet o ITAEnergy entre altres, que facilitaran el procés d'avaluació de les xarxes.

Els resultats del treball proporcionaran mesures d'estalvi que suposaran una millora en l'eficiència energètica del sistema amb la finalitat de poder utilitzar els procediments ací descrits en tot tipus d'abastiments d'aigua a pressió.

Paraules clau: Xarxa d'aigua a pressió. eficiència energètica, metodologia de millora energètica, mesures de millora energètica, vàlvula reductora de pressió (VRP), sectorització, estalvi d'aigua, estalvi energètic.

ABSTRACT

The present Mater Thesis is expected to illustrate the increasing necessity for the improvement of the energy efficiency in pressurized water transport networks. For such purpose, different analyses of the water network are needed in order to understand it and recognize its weaknesses and strengths.

With that purpose, the project will show a methodology devoted to the energy analysis in pressurized water networks, where the different technical aspects that have a direct or indirect influence over the energy efficiency will be examined. With regards to the methodology, it has been developed in Aguas de Valencia group in agreement with the UPV, whose aim is to be able to implement the procedures in the daily operation of the company.

Furthermore, the project will be developed with the use of two potable network case studies: Teruel and Sagunto. The different characteristics and layouts of these water supply networks will allow an analysis from different perspectives so that the methodology can be validated from a practical point of view and from different sources of information.

The work will start with the analysis of the water networks through the use of different software and tools such as Epanet or ITAEnergy, that will ease the assessment process of the networks.

The outcomes of project will provide various energy saving measures that will result in the improvement of the energy efficiency of the system, with the aim of being able to apply the procedures herein described in all kind of pressurized water networks.

Keywords: Pressurized water network, energy efficiency, energy efficiency improvement methodology, energy efficiency improvement measures, pressure reducing valve (PRV), distric metering area (DMA), water saving, energy saving.

CONTENT

Content of documents in this project

- Project body
- Project budget
- Drawings

Project body index

1. Introduction
2. Case studies
3. Methodology
4. Exploring actions
5. Conclusions
6. Future work
7. Bibliography

Project budget index

1. Need for a budget
2. Teruel
3. Sagunto

Drawings

1. General layout of the potable water network of Teruel
2. General layout of the potable water network of Teruel
3. General layout of the potable water network of Teruel
4. General layout of the potable water network of Sagunto
5. General layout of the potable water network of Sagunto centre and North Palancia
6. General layout of the potable water network of Port Sagunt

PROJECT BODY

INDEX

INDEX OF FIGURES

INDEX OF TABLES

1. INTRODUCTION

1.1. Motivation

Water has always been and will be vital for human life. Big civilisations have always risen next to water bodies such as rivers, lakes or even the sea, using the available water for developing essential human activities from agriculture and farming, to cooking and drinking or even sanitation and hygiene. The use of water has also developed along with the development of settlements, villages and cities and, as cities grow and grow, the use of water implicitly grows too. But the explosion of the world's population growth has led to almost quadruple the population in the last seventy years, as shown in Figure 1-1, and the consequences of this in terms of water usage and water resources management are tremendous. Nowadays, water scarcity is a reality in areas where either the water demands are too high, or the water resources are too low. In fact, the most significant problems that many of the cities are facing today are related with the management of these water resources due to the continuous increase of population and specially, the metropolitan areas, whose management is distinctively complicated or the widespread increase of population in tourist areas, that multiply their population in very short periods of time and leave very narrow management margins.

However, it is not population growth the only problem that we are facing today but some other come into place regarding water resources management. Droughts are becoming a very serious problem in some countries and southern areas of the Spanish territory, as well as unexpected longer drier periods in areas where water scarcity has never been an issue. The over-exploitation of aquifers in zones where there is no other solution to extract water make this previously thought unlimited resource indeed limited. And last but not least, environmental contamination is the tip of the iceberg. Countless policies are being applied to solve a major issue that has so many action sides that only global cooperation can, in the long term, succeed in their purposes, as stated in the Paris Agreement (The Convention 2016).

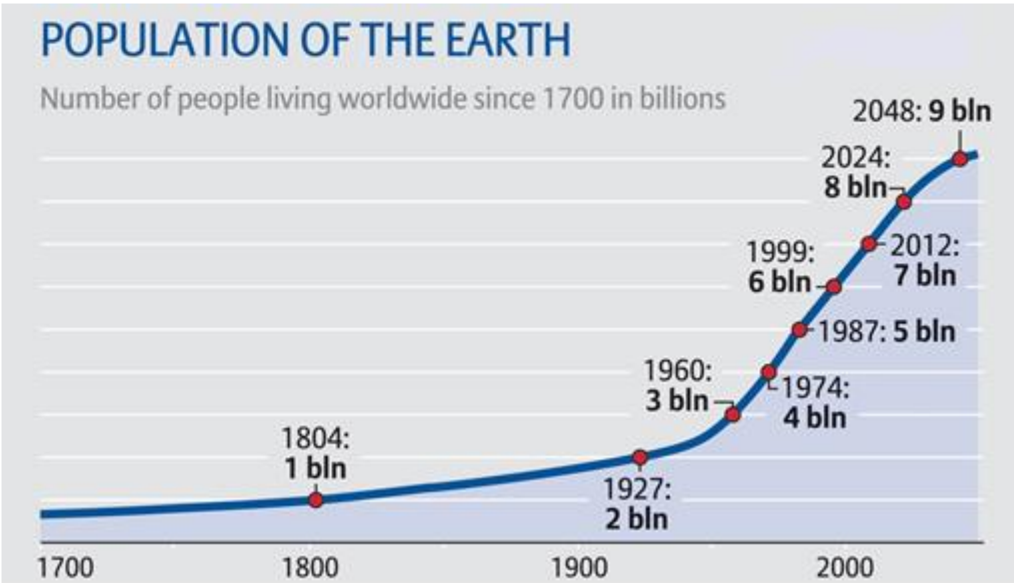


Figure 1-1. Population growth on Earth since year 1700 (Source: United Nations World Population Prospects)

But the unstoppable increase of water demand is not only a problem for water resources but for water infrastructure as well. Potable water networks are nowadays inconceivable without a pressurizing structure that boosts water towards each of the end users, that is, the tap of a sink or the shower in a bathroom. And the increasing water consumptions goes hand in hand with its equivalent energy consumption since, in order to convey the water from the lower to higher parts of a city, or bring the water from the increasingly further sources, electric energy is needed in the form pumping.

The water problem has recently lead the agenda of the United Nations Conference on Housing and Sustainable Urban Development (Habitat III) celebrated in Quito in October 2016. Urban distribution is growing around three and four times more in extension than in population (Nations 2016) and this works against some of the public services such as water supply or waste water treatment in order to function efficiently.

For such reasons, the water sector must reinvent itself as well as reinvent the water infrastructure. Historically, energy consumption has not been a critical aspect in the design of water infrastructure, with designs where the location of the main distribution tank at the tallest point of the city, as a simple example to mention observed in the networks that will be studied, has been proven completely inefficient.

The need for competent, well-organized and above all, efficient water distribution systems is the least that can be done to overcome the overwhelming use of natural resources.

1.2. Water – energy nexus

For years, water has always been used for energy generation purposes. Waterwheels have been utilized long ago to produce energy from a river current and nowadays we use turbines to take advantage of a water fall and generate electricity. This energy generation might even be huge in some cases such as the "3 Gorges Dam" or the "Itaipú Dam" (IRENA 2012). However, water is not only used for hydroelectricity generation but for many other forms of power plants where vapor is used to move the blades of a turbine to eventually produce electricity by means of a generator. Raw material extraction, cleaning processes, cooling of thermal power plants is just a variety of usages that involve water in energy production activities. It is estimated that the total amount of water use for energy production purposes is of 52 billion cubic meters (Spang et al. 2014), what gives a general and obvious picture about the importance of water for energy generation activities. The International Energy Agency places this value even a bit higher and estimates that water withdrawal for energy production in 2010 at 583 billion m^3 (what represents 15% of the world's total withdrawals) of which 66 billion m^3 were actually consumed (United Nations World Water Assessment Programme 2014).

There is no doubt that the most characteristic use of water in terms of energy is related with hydropower generation, although not the only one since it also plays a crucial role in geothermal power, heat pumps, osmotic power or bioethanol. In Spain, the hydraulic generation situates the value in 20.3 MW of total installed power capacity, representing a 20.3% of the total installed power capacity (out of 100.088 MW). See Figure 1-2.

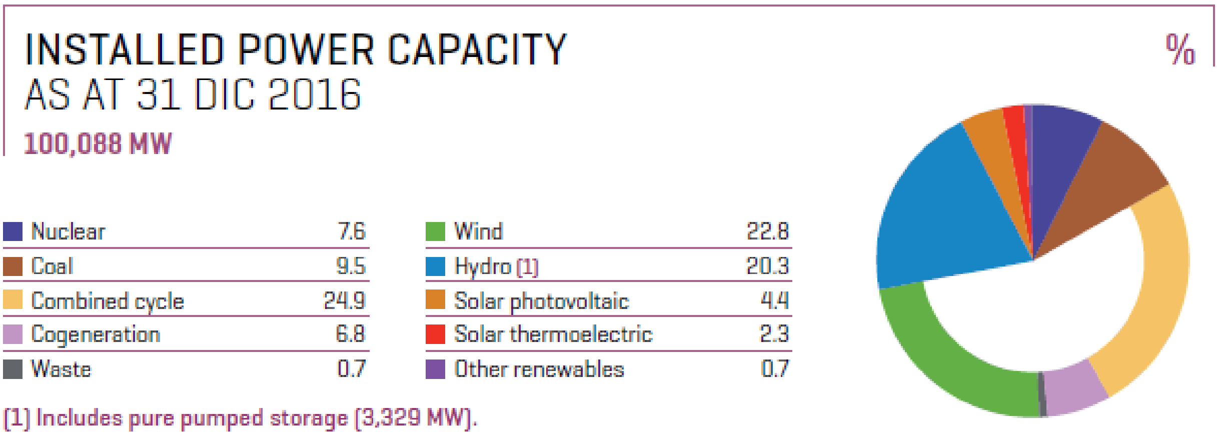


Figure 1-2. Power capacity distribution installed in Spain (Red Eléctrica de España 2016)

According to Red Eléctrica Española, the energy coverage by renewable energies has situated its share to 41% of the total energy generation, compared to 36.9% in 2015, and this increase has been possible thanks to rise of 25.1% in hydroelectric precisely. There is no doubt about the ongoing process in the development of renewable energies however, the overall evolution of the global energy mix does not seem to advance in the rightful direction and reliability in fossil fuels still leads the current guidelines, what yields to high volumes of produced water.

The summary of the previous paragraphs relating water to energy purposes is gathered up in Figure 1-3, where the cooling technologies require a vast amount of water to make possible the eventual energy generation. And the aforementioned estimate of water withdrawal and consumption is expected to rise by 20% and 85% respectively by 2035, based on energy demand rise and the introduction of more efficient cooling technologies that reduce water withdrawal but increase consumption.

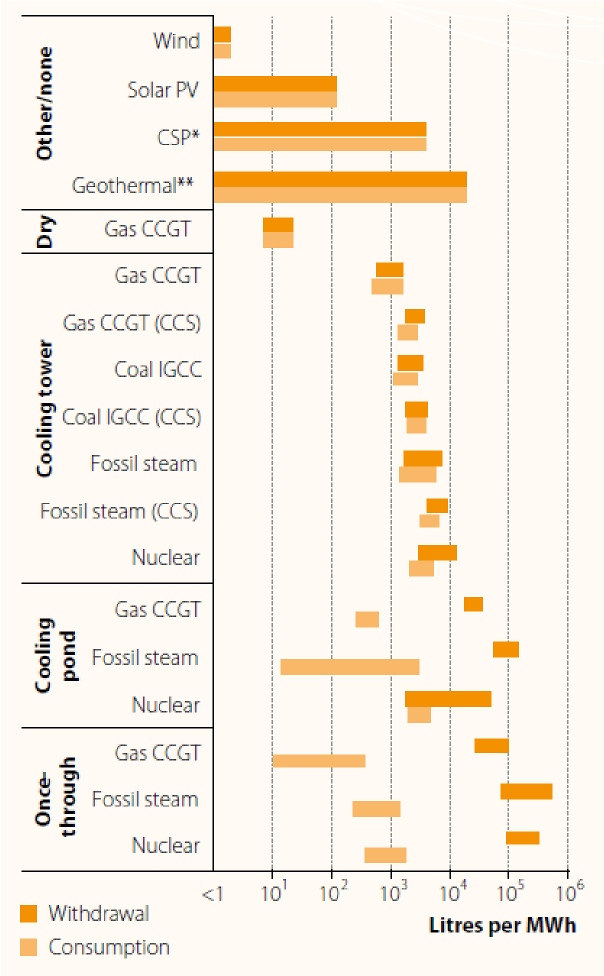


Figure 1-3. Water use for electricity generation by cooling technology (United Nations World Water Assessment Programme 2014)

And honouring the title of this section after stating the importance of water towards energy generation, equally important is becoming the necessity of energy for the complete water cycle to function properly.

The natural water cycle is sustainable itself and only needs gravity to descend water and solar energy to lift it. But the human intervention alters this balance to place potable water at very different places. Thus, energy for water sets the needs of energy for each of the artificial stages in the hydric cycle. From the withdrawal to the final spill, each step requires an energy expense, expressed in kWh/m^3.

An example of the different energy intensities is expressed in Figure 1-4, where different values are recorded according to the network layout and characteristics. The different network examples shown in the graph are described with more detail in the original source: (Lazarova et al. 2012)

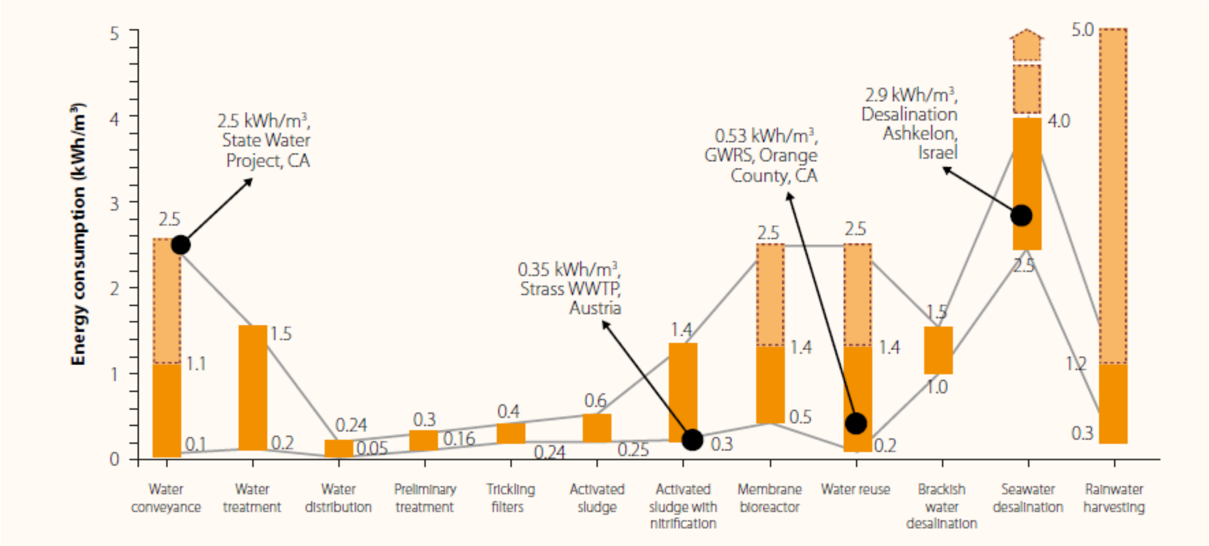


Figure 1-4. Typical energy footprint of the major steps in water cycle management with examples from different treatment plants using specific technologies (United Nations World Water Assessment Programme 2014)

Regarding the Spanish situation, other sources of information are found and depicted in Table 1-1.

Table 1-1. Energy production and consumption indicators for different water uses (Corominas 2010)

WATER USE			KWh/m³
Production	Electric	Hydro (100 m fall)	0.21
		Combined power cooling	345
		Solar thermoelectric power cooling	245
		Thermal power cooling	17.5
Consumption	Irrigation	Pumping (100 m)	0.42
		Localized irrigation	0.18
		Sprinkler irrigation	0.23
	Supply and treatment	Potabilization (WTP)	0.18
		Polishing	0.3 – 0.5
		Tertiary treatment	0.15 – 0.25
	Conveyance	Ebro diversion project (mean head: 723 m)	3.7
	Desalination	Marine water desalination	3.5 – 4
		Salt marsh desalination	1.4 – 1.8

What all the figures can summarize is the increasing importance of energy consumption related to water uses derived from human activity. They highlight the necessity of making an efficient and rational use of water, what is tied to climate change. Recent policies and strategies are directed to fight the issue but sometimes they have proven inefficient. It is, undoubtedly, the path to follow in the upcoming years, with more energy efficient water networks.

1.3. Up-to-date energy efficient management technologies for pressurized water networks

Water companies are becoming each time more aware of the current hydric problematic and are focusing their efforts in trying to develop new technologies that can counteract the harming effects already produced. Aguas de Valencia – Global Omnium is one of the leader companies of the sector involved in the improvement of the energy efficiency in water networks and claims to have state-of-the-art technology in this area. The development of the competitiveness under the philosophy of continuous improvement is one their directions. It is under this framework that this project has been conceived. Global Omnium is applying new protocols and measures that seek to progress in the energy efficiency. One of their flagship technologies is the smart metering. The optimization of the volumetric efficiency in potable water networks by means of new management technology that allows real time data monitoring, with water demand prediction that also enhances better leak control management systems through big data techniques. This leads to countless water savings and eventually, to energy savings.

Another development branch of research is on the improvement of the water processes that are implicated in potable uses: extraction, transport, potabilization, sewage, polishing… by the improvement of the process itself and the use of renewable energies that eventually lead to more energy efficient uses. By means of the implementation of energy management systems these processes can be better monitored, studied and controlled.

There is another body in charge of promoting energy efficient techniques for the different sectors. The Institute for Energy Diversification and Saving (IDAE) focuses its efforts in developing different guidelines for the correct use of energy in terms of efficiency. In the last two action plans of 2008 – 2012 and 2011 – 2020 it can be found the different measures and procedures to follow for the many economic sectors covered in the action plan. But only one stream is related to energy use in activities involving water expense: the agricultural sector.

The measures start from boosting the shift of sprinkler irrigation systems towards localized irrigation or promoting the realization of energy audits to irrigation networks. The first measure proposed is not applicable to potable water networks, whereas the second one, although applicable, still needs some polishing to produce reliable results as the methodology lacks some intrinsic characteristic of water networks that are not considered in the IDAE guide. The complete procedure is described in "Protocolo de Auditoría Energética en Comunidades de Regantes".

A part from the two above-mentioned currents, another starting point with regards to energy efficiency in water networks is set by any other water company that manages water networks. Each of these companies have their own procedures, software and management techniques however, the competence set among these companies places an important barrier to develop more efficient techniques jointly.

This work has been developed under the agreement between Aguas de Valencia – Global Omnium and the ITA department of the Polytechnic University of Valencia, in an internship period that has allow to know the state of the art of the technology and the need for the improvement of energy efficiency techniques.

1.4. Objective

When trying to improve the energy efficiency of a pressurized water supply network, not complete bibliography is found that comprises all the different aspects or elements that play a role that impacts the energy efficiency of this water network. The bibliography is usually found separately. Leakage assessment is one of the common strategies that reduces the energy consumption or reducing pump station inefficiencies is another usual approach for water systems improvements. However, the fact of having a complete methodology or tool for assessing water networks allows the user to get a complete picture of the system.

The main objective of this work is to validate a methodology quite recent so far that Aguas de Valencia – Global Omnium is trying to develop together with the UPV so that it can be implemented in its daily basis operation more and more often. By means of practical case studies, this methodology will allow to know and understand the water network, to identify and assess the weakest points as well as recognize the strong pillars of the water system.

The outcomes of the project will lead to the application of direct actions or measures to the water networks under study although sometimes more detailed analyses about a measure to be taken will be needed. Furthermore, this methodology is aimed to reach favourable results that will eventually lead to a fast economic investment recovery. Yet, the calculated improvement margin will be sometimes small and therefore, the investment benefits scarce. It is for that reason that the methodology and tools that have been developed all along the document are of great aid for the purposes mentioned above, and this work will try to put in practise a series of steps and use a number of case studies to show the results. At the end of the project, the reader will have an accurate source of information regarding water supply network analysis, as well as real application examples that have been studied in place.

Additionally, the study will be a guide of the limitations of the methodology. As it will be described, a package of tools is used throughout the work in order to reach effective results. And the use of the different tools herein described that enhance the development of a proper water network analysis is usually limited by the scope or possibilities of these tools themselves rather than the methodology itself. So, in order to improve the results, if needed, the trust in a complete tool package is necessary and thus, the improvement of the software tools is required too.

On the other hand, water companies usually have their own management tools to function and operate in their daily basis. Their practices do not always coincide and they apply procedures that may differ from each other while having the same final objectives. It is for that reason that one important objective of this study is to unify water network energy assessment in a single and generalized methodology that will ease the definition of goals, the standardization of different procedures and eventually, cost reduction benefits.

It is obviously not possible to completely unite water network assessment in a single package. Furthermore, the different strategies and purposes of each water company undoubtedly would lead to discrepancies in such a complex and big field as water management is. However, the final aim of improving the energy efficiency of a pressurized water network and the different ways for doing so are never differ that much among different pressurized water network topologies.

Moreover, it is important to note that the results obtained in this work and the descriptions developed herein can also help to improve the methodology itself in order to make it more efficient and practical in the future. It is for that reason that not only one case study is analysed but two of them. The first objective is clear, to search for different solutions that will ameliorate the two networks, but secondly, the comparison between both will prove the validity of a methodology for different network configurations and characteristics, and will allow to search for improvements in the methodology itself.

2. CASE STUDIES

The analysis methodology that is described in this project is supported by two case studies, both of them are referred to a pressurized drinking water network. Although a detailed comprehension of the network is always necessary as long as an energy assessment is to be done to any water supply network, describing these two layouts in detail is not part of the main goal of this document. Furthermore, different explanations will be given at every step of the analysis for each of the case studies, so a better understanding of the networks will follow as the work is developed. In any case, a general description is given below so that the main characteristics of both systems are comprehended.

Among the different supply networks that have been analysed and studied during the research phase of the work, the chosen two have special characteristics, features and issues found over them that make them liable and appropriate to be assessed.

First of all, there is the topographical approach; Teruel has high mean elevations in general, but along the network one can find different elevations for consumption nodes as well, what makes this network difficult to manage in terms of topographic energy. Furthermore, there are end tanks far away from the main source what is usually translated in water losses. The high pressure governing the grid in the lower nodes is also translated in water losses. Finally, one of the main issues for this network is its modelling. Due to the complexity of the network it did not exist an accurate mathematical model that allowed a proper energy assessment with the existing software, for that reason, one of the major tasks has been the update of the mathematical model.

On the other hand, Sagunto already had a robust mathematical model that only needed a few minor updates such as water consumption updates or leaks updates. But what makes interesting this network are the current issues that they are experimenting. The volumetric efficiency for such system is poor and leakages are high due to, mainly, the high pressures of the network. The good point of this network, is its easy disaggregation into two completely isolated supplies (Sagunto City Centre and Port Sagunt). The high number of water meters installed along the network and the disaggregation allows a proper analysis and a faster comprehension of the problems. Furthermore, in Sagunto some updates are currently being applied what also allows to verify the improvements in the model with real information.

So, the fact of choosing two different case studies and not simply just one lies on the different layouts and problems governing the current networks. What allows as well to verify how the steps developed all along the document help to understand the networks, analyse them and check whether if the applied improvements have a tangible impact or not.

Since both networks will give different energy results, it will be useful to see when a measure applies better to one water supply or another, and this is an interesting point to verify with the current technology that will be explained later on. For such reason, although this work is applied to two specific case studies on how to improve their energy efficiency, it is thought to be applied to most of pressurized water networks.

2.1. Teruel

Teruel is a Spanish city located in the south of Aragon and eastern Spain. It is the capital of the province with the same name. It has a population of 35.564 (INE, 2017) making it the least populated provincial capital of Spain. It has an extension of 440.41 km^2 and an elevation of 915 meters above the sea level.

Figure 2-1. Map of Spanish provinces with Teruel in red

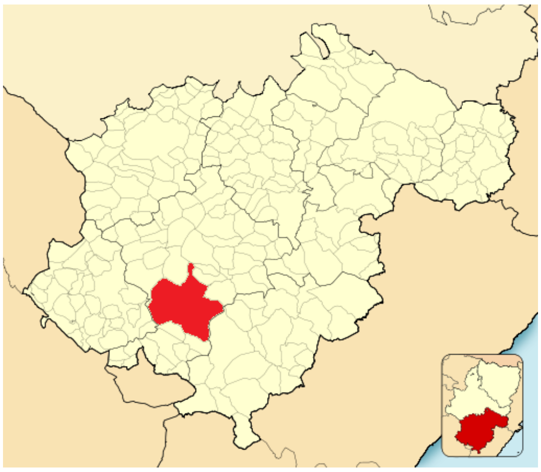


Figure 2-2. Location of Teruel in the province

Teruel receives the confluence of the rivers Alfambra and Guadalaviar, the latter receives the name of Turia from Teruel to its end in Valencia. The rivers belong to the Júcar Hydrographic Confederation.

The climate of Teruel is humid subtropical bordering on a cold semi-arid climate according to the Köppen climate classification. In general, summer temperatures are mild and winters are cold. Average precipitation in Teruel is 369 mm year (López Martín et al., 2007).

The demographic evolution stabilizes since the year 2008:

Table 2-1. Demographic evolution of Teruel since 2007

2016	2015	2014	2013	2012	2011	2010	2009	2008	2007
35,564	35,590	35,675	35,961	35,841	35,288	35,241	35,396	35,037	34,236

For that reason, the domestic water consumption is not expected to raise in the coming years.

Teruel is a small region in terms of economic activity. Traditionally, the main economic sectors have been the agriculture of the cereal and coal mining. Nowadays, the economy in Teruel is based on tourism but also on the energetic sector and food and agriculture industry.

Water consumption in Teruel is very steady throughout the year. Just in the summer months, it raises due to irrigation to satisfy the agriculture industry in the drier periods.

In the network of Teruel it can be distinguished and well differentiated two parts. One of them is the water source itself, pumping stations and water treatment station, that will be called from now on "bulk supply" and the second part that comprises the main water tanks and the city of Teruel itself. It will be called from now on "retail water supply". Figure 2-3 shows a general diagram of the network.

The approximate length of the piping network of Teruel is 185 km.

- Bulk supply

The bulk supply comprises the two water sources of the city of Teruel. The first one and main one is the reservoir of Arquillo and the second one is the well of Concud and Caudé, two small settlements on the outskirt of the city of Teruel.

The water supply percentage from the reservoir and the well is 78 % and 22 % respectively and approximately. This is translated in approximately $4.1 \cdot 10^6$ m^3 of system input water volume in year 2016.

Water is pumped from the reservoir to the header tank and then is sent by gravity to the Agua Bruta tank. During this route, water is supplied to the small town of El Campillo and the main industrial state of Teruel.

From the wells of Concud and Caude water is supplied to these small towns and then is sent to a small tank called “Caja de Cerillas” before being pumped to Agua Bruta where it joins the water coming from the reservoir.

From Agua Bruta water is then pumped to be treated in the water treatment plant according to the needs of the network.

- Retail water supply

Once water has been treated, it is stored in the Old and New tanks, both connected between them and acting as the main tanks of the network. From these two tanks, from now on Old tank since they act as one big tank, water is sent by gravity to one part of the city of Teruel and to another big tank called Cemetery. From this tank, water is supplied to the rest of Teruel as well as to the end tanks of some rural areas on the outskirts of Teruel.

It must be said that the water treatment plant, Agua Bruta pump station, Caja de Cerillas and the Old and New tanks are all placed in the same plot but with different elevations, being Agua Bruta pump station the lowest point of all and thus water needs to be pumped. The terrain irregularities of the plot make this area critical, being most of the pumping developed here.

In general terms, the drinking water supply network of Teruel is described as written above. More detailed information will be given later on in the different sections of the work. And the calculations of the energy efficiency studies carried out will ease the comprehension of the network as well.

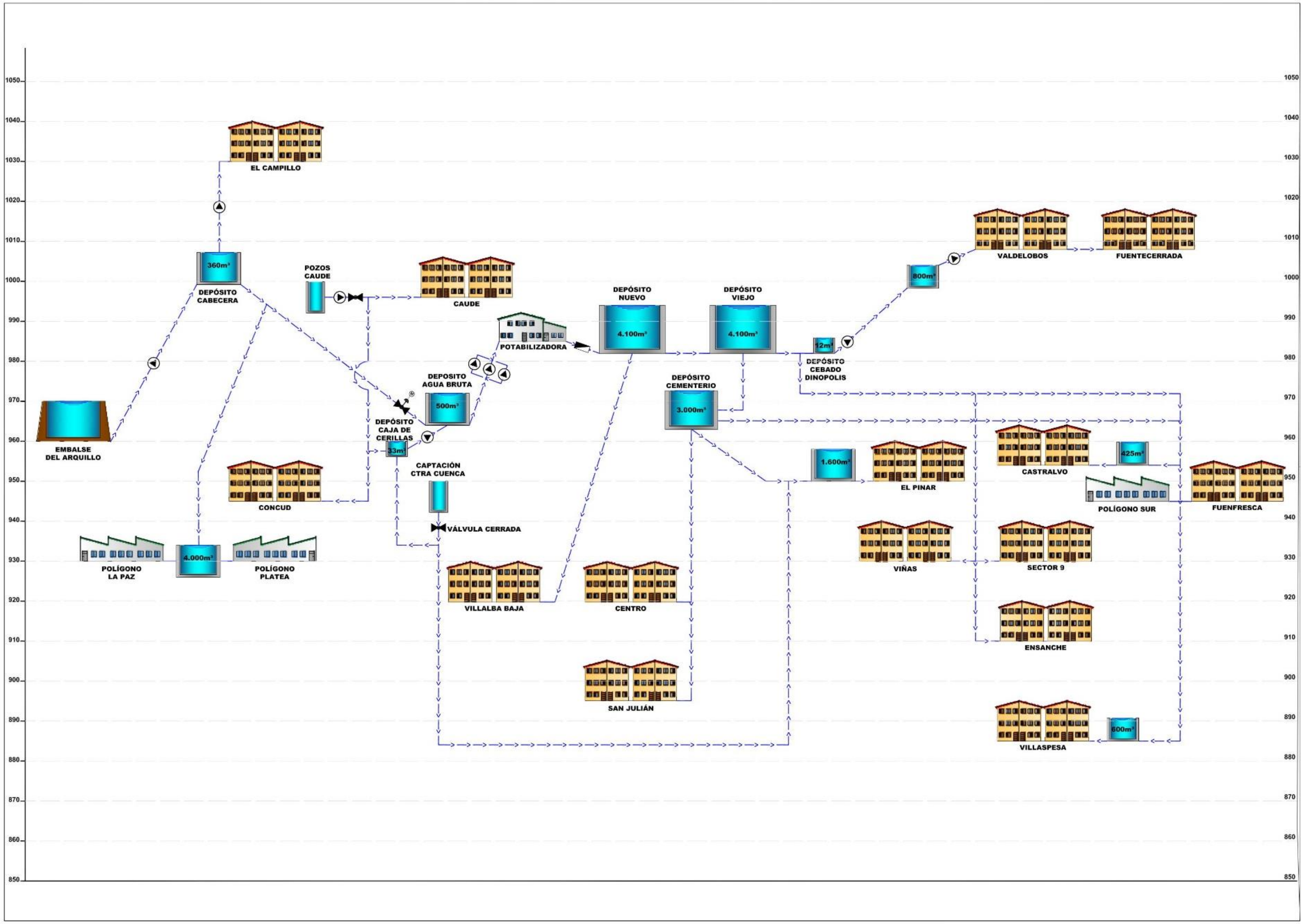


Figure 2-3. Teruel network diagram

2.2. Sagunto

Sagunto is a Spanish town in the province of Valencia in Eastern Spain. The population of Sagunto is 64,439 in the year 2016 (Ine.es, 2017). It has a total extension of 132 km^2 and an average elevation of 49 meters. However, there are two differentiated areas; one of them Sagunto city centre with elevations between 40 to 100 meters and Port Sagunt with elevations between 0 and 30 meters above the sea level.

Figure 2-4. Map of the Spanish provinces with Valencia in red

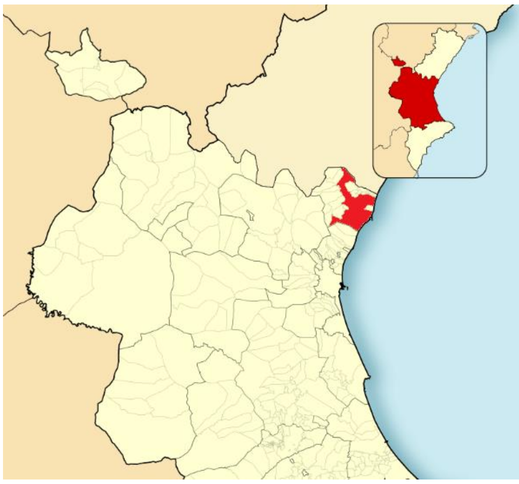


Figure 2-5. Location of Sagunto in Valencia

The only river that actually flows through is the river Palancia. However, at its pass in Sagunto it already arrives dry so it is just used for irrigation purposes in suburban fields and for parks all along the city.

Sagunto receives its water from the Tous dam through the "Júcar – Turia Canal" and the Turia – Sagunto conduction up to a big raw water reservoir of 150,000 m^3 capacity, where the water treatment plant is located. Water is supplied by the Júcar Hydrographic Confederation.

Historically, the population of Sagunto has steadily increased until year 2008 when it was stabilized.

Table 2-2. Demographic evolution of Sagunto since 2007

2016	2015	2014	2013	2012	2011	2010	2009	2008	2007
64,439	64,944	65,003	65,190	65,238	65,595	66,259	66,070	65,821	63,359

Most population is concentrated in Port Sagunt and then in Sagunto city centre.

Traditionally, the economy in Sagunto is based on the ferrous metallurgy industry, citrus exportation and port trade commerce. Today, there exist some industrial states with more or less occupation. On the one hand, there are Sepes and Ingruinsa that are fully operational and belong to the hydraulic network of Port Sagunt. On the other hand, there are Camí la Mar and Parc Sagunt that form a different and independent network and have a low occupation rate. However, they have considerable water consumptions.

The network starts at the water treatment plant located at 52 meters above the sea level. The approximate length of the piping network is 270 km.

The network is well differentiated in three different parts.

There is one pump that carries water to a tank at 110 meter and then is distributed to Sagunto city centre and North Palancia. Both urban centres are interconnected but separated by the river Palancia and therefore, they could be isolated from each other if necessary.

On the other hand, there is another pump that supplies water to a distribution storage tank at 75 meters high. This tank regulates the demand of Port Sagunt and delivers the water accordingly. After this tank, water goes to a break pressure tank at 55 meters. Otherwise, pressure at Port Sagunt would be too high since elevations are around 0 and 30 meters above the sea level. Integrated in this network, water is also distributed to two industrial states of Ingruinsa and Sepes, but the tank of Sepes is not operational today.

The same pump that supplies water to Port Sagunt is used for providing water to the other two industrial states of Camí la Mar and Parc Sagunt. When the pump is functioning, water goes directly to industrial states, when the pump is stopped, then water is provided from the storage tank at 75 meters.

Finally, there is another network that supplies water to an area called L'Almardà with another pump. This network will be left out of the study since this is a beach area that basically consumes water just in summer. It is a very seasonal consumption that will bias the results. For that reason, it makes no sense to include it in the whole analysis but needs an individual assessment if considered appropriate.

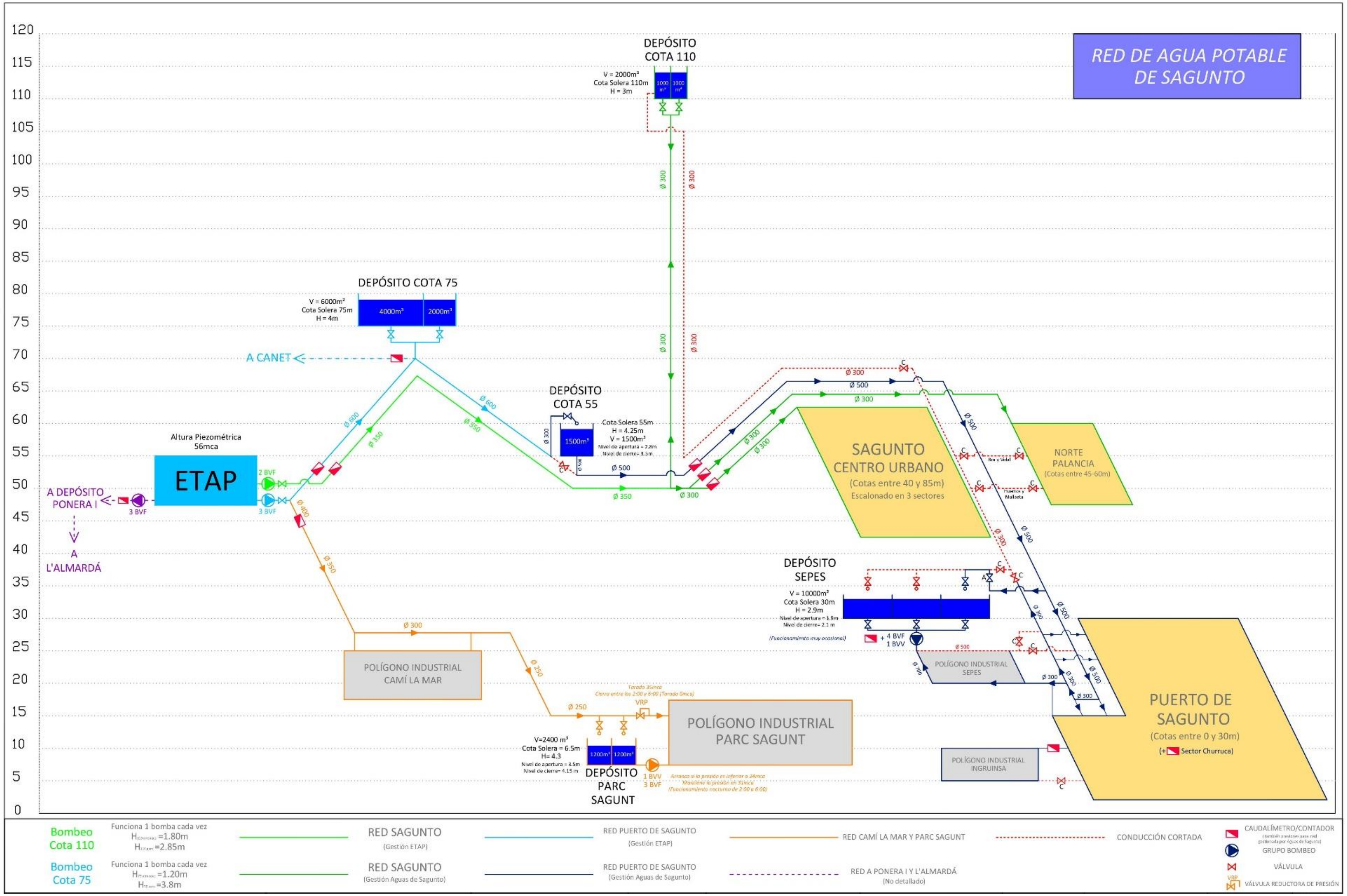


Figure 2-6. Sagunto network diagram (Lozano 2015)

3. METHODOLOGY

The work done all along this document is referred to a pressurized water network analysis methodology (Cabrera et al. 2015). In general, there is no difference whether if the water network is an irrigation network or an urban water supply system since both of them follow the same hydraulic properties and principles of a pressurized flow. The case studies examples will be applied to urban drinking water networks but the procedure can be of the same aid for irrigation systems. As long as the technology is developed, a complete analysis will derive in an assessment of the water supply of the network and its efficiency.

It cannot be forgotten that this project has always been focused on the case studies, so the work frame is that of the verification of the methodology through these case studies.

It is not in the scope of this project to describe in detail the methodology, although it is of necessity to explain the general structure of it. Furthermore, the different steps of the methodology will be developed as the case study examples are shown and with more detailed equations in the following sections.

Figure 3-1 shows a flowchart of the different steps to follow when assessing a pressurized water network. As mentioned before, no single differences lay under this analysis when looking at either an irrigation system or a drinking water supply network.

Analysing the flowchart from top to bottom and from left to right:

- **Assessing the initial requirements**: With all the initial information of the network, input data, it should be possible to establish the minimum required energy by the users of the system. It is assumed that minimum water demands are logical and optimal. Therefore, water demands are given. But it should be necessary to assess first if these demands are optimal.
- **Diagnostic left**: With the minimum required energy and the energy that the system is really consuming, calculating an ideal efficiency (η_{ai}) as well as the real efficiency (η_{ar}) of the system is possible. Between these two efficiencies there will be a compromised value that will be the objective efficiency ($\eta_{ar,o}$). If the difference between the objective efficiency and the real efficiency is low, there will not be room for improvement in our system and the assessment will be done. On the contrary, if there exist an important margin between the ideal efficiency and the real one, further actions will need to be done.
- **Diagnostic right**: The complementary value of the ideal efficiency of the system is the topographic energy. It depends on the topography of the area and the layout of the system. Addressing it will be a matter of how important this value is.
- **Analysis left**: Since the diagnostic just gives a preliminary information about the status of the network, a water audit and an energy audit are needed for more detailed information about how energy is lost in the system. This step is of great importance; audits will assess any aspect of the network and will define the type of measurements to take.
- **Analysis right**: If the topographic energy is high enough to be assessed independently, it is important to see how this topographic energy is distributed. Supplying pressure to high points of the network results in a high pressure in the lower points of the network. It is therefore

convenient to analyse if decoupling and supplying the water to the high part of the network is a good option.

- **Exploring actions left**: According to the audit's results, there will be actions to be taken in order to improve the efficiency of the system. If it is about an operational improvement action, it will mean that no investment is required. Changing the working point of the pumps is the most common action. On the other hand, and structural action will imply an investment cost so that the layout of the water network will change.
- **Exploring actions right**: Since topographic energy is not avoidable due to the different elevations of the network, it will be necessary to analyse whether if it is possible to reduce this energy by means of pressure reducing valves (PRV) or recover this energy by means of pumps working as turbines (PAT). The latter is a less developed technology although some works have already been done (Del Teso March 2016).
- **Taking decisions**: This step can be analysed jointly for both columns. It is a cost – benefit analysis that will determine if the action to be done makes sense or not. It is not just a matter of money but different aspects are to be considered. Return on investment, environmental impact analysis, water savings, social impacts… If the action has been done, this allows recalculating again the new efficiency of the network. Seeing how much the network has improved will give a final efficiency and losses indicators (η_{ar}, λ_{wl}, λ_{wf}, λ_{wp}, λ_{wo}).
- **Final label**: Although it is not in the scope of this study, and because this point has not yet been developed, the idea at the end of the whole process id to label pressurized water supply networks the way it is done with house energy labelling. According to how energy efficient a network is, it will be labelled accordingly. However, depending on the network topology, each system will have a maximum efficiency to be reached, so the label scale should be unique for every system.

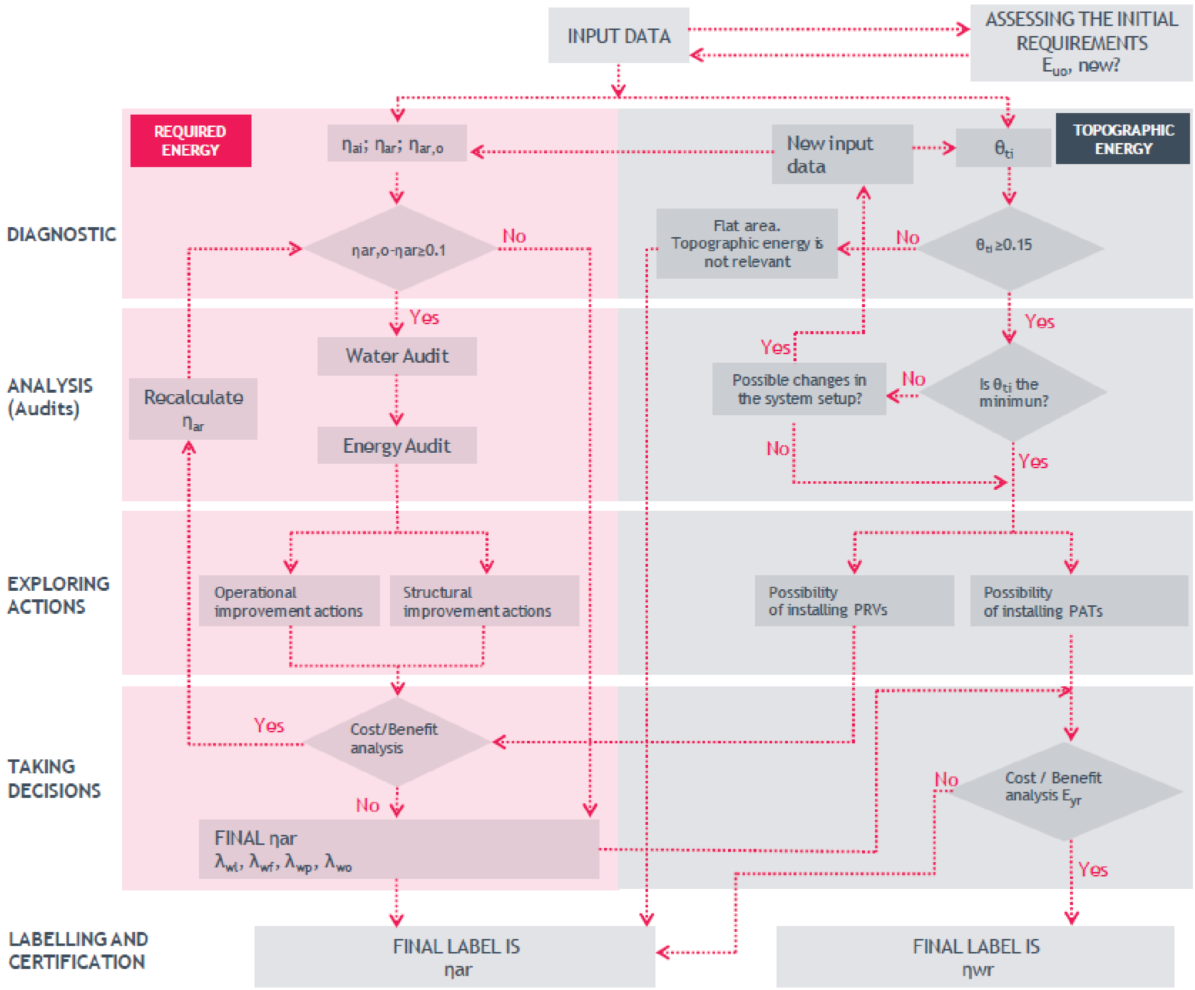


Figure 3-1. Methodology flowchart. (Gómez 2016)

3.1. Diagnostic

To assess any system, there has always been a very well-known and used concept, as it is efficiency. Applied to any control volume, the energy that should be consumed by this control volume divided by the energy that is truly supplied to the control volume will give an overall performance of how energy is being used, an efficiency.

As a first step to an analysis process, the diagnostic will tell us about the current state of the system. There are of course some notions associated to energy consumption of a water system that must be explained, but in order to calculate an efficiency indicator, everything is reduced to ideal energy consumption and real energy consumed.

To calculate the efficiency of a water network, first, the required energy must be obtained. The energy that the system requires is subject to the layout of the network and every single network will have a different layout and therefore, a different energy request. Then, the energy that is truly entering the system is easier, it can be read from the electric bill, although the natural energy must be accounted for as well.

In Figure 3-2 it is represented a simplified diagram of an ideal pressurized water supply network without excess of energy. The most important points of the network are:

- A water source: From which water is supply to the system. It can be a dam, a reservoir, a water tank, a well, etc. The piezometric head h_{ni} is needed.
- A pumping system.
- The highest and the lowest nodes: Z_h and Z_l.
- A generic node: Z_j.
- The lowest pressure node that will be critical: Z_c. $Z_c = Z_h$ in an ideal system.

If the system is ideal, it means there are neither friction losses nor water leakages. It is for that reason that the piezometric line is straight all along the system. Since there is no excess of energy, this means that the critical node receives the necessary pressure associated to its elevation Z_h plus the service pressured P_0.

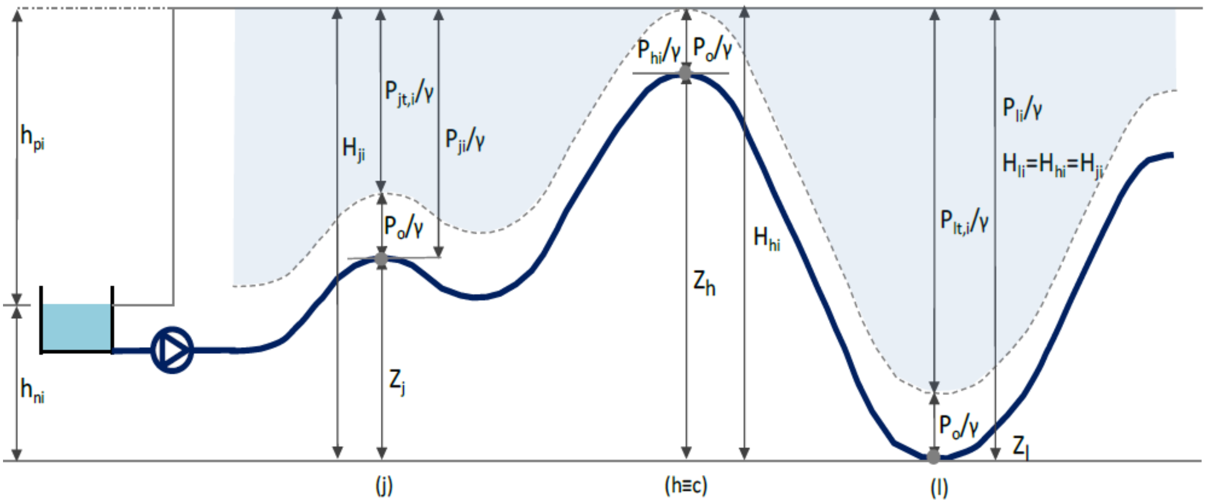


Figure 3-2. Ideal water system diagram. No excess of energy (Cabrera et al. 2015)

If the continuity equation is applied to the ideal system above, the total injected water volume by the pump station (V) is equal to the sum of the demanded water by each of the nodes of the system (v_j); $V = \sum v_j$. Therefore, to obtain the minimum required energy by the users:

$$E_{uo} = \gamma \sum v_j \left[(z_j - z_l) + \frac{p_0}{\gamma} \right] \tag{1}$$

And to obtain the topographic energy that is constrained by the highest node:

$$E_{ti} = \gamma \sum v_j \, (z_h - z_j) \tag{2}$$

If the system is supplied with an excess of energy, the critical point will receive the minimum required head, plus the service pressure plus the excess:

$$E_{ei} = \gamma V \frac{(p_{hi} - p_0)}{\gamma} \tag{3}$$

Being p_{hi} greater than p_0 and γ is the specific weight of water ($9810\,\frac{N}{m^3}$).

Therefore, the total supplied energy in an ideal system:

$$E_{si} = E_{uo} + E_{ti} + E_{ei} \tag{4}$$

So that the efficiency indicator is defined as follows:

$$\eta_{ai} = \frac{E_{uo}}{E_{si}} = 1 - \frac{E_{ti}}{E_{si}} - \frac{E_{ei}}{E_{si}} = 1 - \theta_{ti} - \frac{E_{ei}}{E_{si}} \tag{5}$$

If it is assumed that no energy excess is provided, then the ideal system efficiency and the total topographic energy percentage θ_{ti} are complementary. A very flat system will have an ideal efficiency close to 1 whereas a system with different elevations will have a considerable percentage of topographic energy.

The only situation left to explain is that of a real system. In a real system there exist losses, and to overcome these losses, more energy needs to be supplied to the network at header, see Figure 3-3. The different kind of losses that can mainly be found on a pressurized water supply system are:

- Pumping energy losses (E_{rp}) due to inefficiencies in the pump station.
- Friction energy losses (E_{rf}) through pipes, valves or other elements.
- Leakage energy losses (E_{rl}) when water is leaking the network and this water has an embedded energy that is lost. Furthermore, apparent losses must also be taken into account in this point, such as those due to inefficiencies in the water meter.
- Other energy losses (E_{ro}) through break pressure elements.

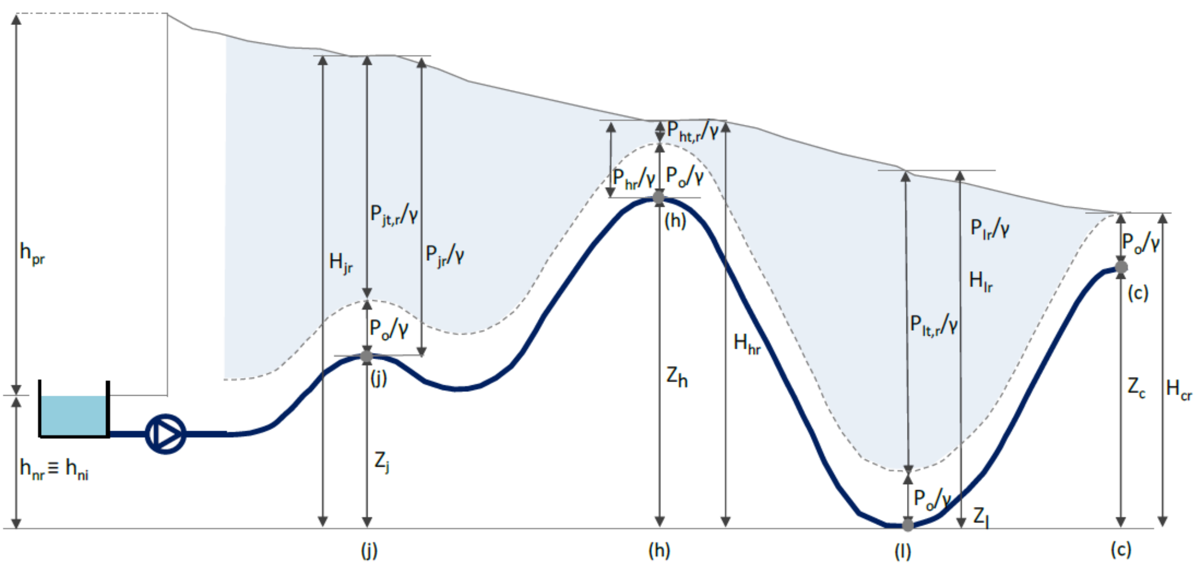


Figure 3-3. Real water system diagram. No excess of energy (Cabrera et al. 2015)

The supplied energy in a real water system, without excess of energy:

$$E_{sr} = E_{uo} + E_{tr} + E_{rg} = (E_{uo} + E_{tr}) + (E_{rp} + E_{rf} + E_{rl} + E_{ro}) \tag{6}$$

So that the real efficiency of the system:

$$\eta_{ar} = \frac{E_{uo}}{E_{sr}} = 1 - \frac{E_{tr}}{E_{sr}} - \frac{E_{rg}}{E_{sr}} = 1 - \theta_{tr} - \lambda_{rg} \qquad (7)$$

Since it is not of the scope of this paper to describe the theoretical development of the equations and more explanations about the energy assessment of ideal and real systems with and without excess of energy, here it has been shown what is necessary for a comprehensive reading of the work. For more information refer to (Cabrera et al. 2015; Gómez 2016).

As it has already been mentioned in the methodology flowchart, the network will be object of study if it exists a clear difference between η_{ai} and η_{ar}. Since η_{ai} is unachievable, there will be an intermediate and reasonable objective efficiency that will be our target to reach when implementing betterments to the network.

3.1.1. Energy diagnostic calculation tool. EAGLE

EAGLE (Energy Assessment of Global Pressurized Water System) is a simple tool that allows the user to carry out an energy diagnostic of a pressurized drinking water distribution network or irrigation network. The tool is a MS Excel sheet that shows, from basic input data of the system, the results of an energy diagnostic that will ease decision making towards energy efficiency improvements.

In order to come up with a diagnostic, EAGLE proposes a series of steps:

Figure 3-4. Diagnostic steps layout

- Typology: It allows the user to choose between four different typologies according to the layout of the network. It must be chosen the one that fits better our system.
    - Gravity supply network
    - Direct pumping supply network
    - Reservoir – Tank – Network
    - Network with different inputs
- Characterization: Here it is included a series of properties of the system. The analysis period (day, month, year) that will condition the resulting units (kWh/year, m^3/day …), the type of network (urban, irrigation), the total input volume…
- Configuration: The necessary data to obtain a good diagnostic depend on how much information the user has about the network. In these case studies, maximum information for this point is available. Therefore, elevation and demand of each consumption node will be introduced in the tool. Furthermore, the service pressure (minimum required pressured) is also needed. With the sum of all the demands of each node, the total billed consumption is obtained.
- Energy data: For this step, the energy supplied to the system is needed. Normally from the pump stations, the total energy consumption can be obtained directly from the energy bill. If there are

different pump stations, it must be specified how much water is supplied by each one, being the sum the total input volume. Furthermore, the head given by the pump can be also given so that pump efficiency can be calculated.

- Diagnostic: With all the data introduced, the results of the diagnostic will show up in this screen. The tool will tell the user about the different energies and efficiencies of the network, taking always into account that this is a diagnostic and, since data is very generic, results will be an approximation. One will be able to see: E_{uo}, E_{ti}, E_{ei}, E_{si}, E_{sr}, η_{ai}, η_{ar}.

The diagnostic proves itself to be an initial tool that helps to give a general picture of the system. For complex networks, the results obtained will need of further detailed analyses to better assess the network. In these complex systems, the difficulty of defining an appropriate control volume leaves the diagnostic out of its initial aim, although a first overview can be obtained.

3.1.2. Case study diagnostic results. Teruel

Table 3-1 shows the results of the first step of the methodology, the diagnostic. From this, two main things can be discussed. First of all, the efficiency terms: as it is described in the methodology, the system efficiency allows the user to determine whether if the system is suitable for further study or not. It must be taken into account that the diagnostic is more like a preliminary study rather than an accurate assessment. Input data is basic and the topologies offered by the tool do not cover all the different possibilities than can exist in a supply network more or less important like this one. In any case, it can be observed that there exists a difference between the ideal and real efficiency that leaves some margin to improve the latter.

Table 3-1. Diagnostic results of Teruel

Ideal energies	Minimum required energy by users	E_{uo}	757,209.87	kWh/year
	Topographic energy	E_{ti}	904,385.94	kWh/year
	Excess energy	E_{ei}	0	kWh/year
	Total supplied energy	E_{si}	1,661,595.80	kWh/year
Real energies	Natural supplied energy	$E_{sr,n}$	1,212,947.73	kWh/year
	Shaft supplied energy	$E_{sr,p}$	1,113,025.00	kWh/year
	Total supplied energy	E_{sr}	2,325,972.73	kWh/year
Efficiencies	Ideal efficiency of the system	η_{ai}	0.46	-
	Real efficiency of the system	η_{ar}	0.33	-

The second main aspect that can be observed is the amount of topographic energy supplied to the system. As already explained, the complementary of the ideal efficiency is the topographic energy being the excess energy equal to zero. This energy comes from the difference in elevation from some nodes to others in the network and is supplied to the lower users in the form of overpressure. It is a very large amount of topographic energy that should be analysed.

This diagnostic also has two different perspectives; on the one hand, it rapidly gives the user a view where it tells you about the available room for improvement, which is a very good point, but on the other hand, it is difficult to distinguish which part of the network has the greatest amount of losses. For that reason, it is not a bad idea to carry out different diagnostics. In this case, it can be differentiated between a diagnostic of the bulk supply and the retail supply, but many others can be also done to the different sectors of a network, if there are, or to final branches or any control volume from which the necessary input data is known. However, for sake of simplicity of this study, these extra analyses will not be shown here. Additionally, it is of the engineer's decision-making capacity to determine how many diagnostics are needed. The benefits here lay under the easiness of carrying out these diagnostics.

As a general summary of the diagnostic, more energy than the necessary is being supplied to the system so, the next step is to determine where these losses are taking place in order to reduce them. However, a deeper analysis is needed later on for more specific results.

EAGLE has a pre-audit section/window as well as a last step. Here, the tool differentiates between friction and other losses, pumping losses and leakage losses. However, they will not be analysed through the EAGLE since detailed audits will follow that will give much more information about the energy losses than this pre-audit window. In addition, as already mentioned, this is not the aim of EAGLE, but just to give an overall behaviour of the network to determine if further analyses are necessary. Furthermore, a part from this pre-audit not having the desirable accuracy, in order to actually get results, one needs more detailed input data instead of the global values that are just needed to get a diagnostic.

From my view, this pre-audit window might be more useful for irrigation or simpler water supply networks where information is also simpler. Whereas for such complex networks like this one, this pre-audit does not make much sense and it is needed a further and deeper analysis.

3.1.3. Case study diagnostic results. Sagunto

As it has been explained section 2.2, in the case study of Sagunto, there exist two decoupled systems: On the one hand Sagunto city centre and North Palancia (Sagunto CC + NP) and on the other hand Port Sagunt and the industrial states (Port Sagunt + IS). The latter could have also been decoupled in two, Port Sagunt for one side and Industrial States for another, but the input energy for both comes from the same source. Due to this well differentiation, Sagunto will always be studied in two. Therefore, two diagnostics will follow. This way it is easier to determine where the improvement margin is, however, in such big networks both of them will allow significant betterments.

In Table 3-2 the results for the first diagnostic of Sagunto CC + NP can be found. In terms of energy distribution, it can be observed how more than 50% of the energy is assigned to topographic energy, what is translated in 46% of real system efficiency. In this case, there exist a slight negative energy excess. In order to understand the sense of the negative sign, it is necessary to explain a bit the network layout. The main tank of the network is placed at 110 meters as it can be seen in Figure 2-6, the service pressure established for this network is set to 20 meters of water column and the highest node of the network has an elevation of 93 meters. These 93 meters plus the 20 m.w.c. is greater than the 110 meters available for the consumption nodes. Therefore, the least favourable node will not receive 20 meters of service pressure.

Table 3-2. Diagnostic results of Sagunto City Centre + NP

Ideal energies	Minimum required energy by users	E_{uo}	118,219.04	kWh/year
	Topographic energy	E_{ti}	139,947.84	kWh/year
	Excess energy	E_{ei}	(-)683.27	kWh/year
	Total supplied energy	E_{si}	257,483.61	kWh/year
Real energies	Natural supplied energy	$E_{sr,n}$	115,737.61	kWh/year
	Shaft supplied energy	$E_{sr,p}$	468,300.95	kWh/year
	Total supplied energy	E_{sr}	584,038.56	kWh/year
Efficiencies	Ideal efficiency of the system	η_{ai}	0.46	-
	Real efficiency of the system	η_{ar}	0.20	-

In Table 3-3 it is displayed the diagnostics results for the network of Port Sagunt plus the industrial states of Ingruinsa and Parc Sagunt. At first glance, what stands out here is the high topographic energy again, what leads a small room for the ideal efficiency of the system, being of 43%. The 57% remaining is to be recovered or at least reduced because the pressure excess will be too high to be handle by the network. The margin that exists with the real efficiency of the network is big enough to think that there is room for improvement. And the great amount of topographic energy also leaves margin to reduce it and therefore improve the ideal and real efficiency of the system. How this topographic energy is reduced will be seen along the project.

Table 3-3. Diagnostic results of Port Sagunt + IS

Ideal energies	Minimum required energy by users	E_{uo}	411,368.10	kWh/year
	Topographic energy	E_{ti}	552,661.89	kWh/year
	Excess energy	E_{ei}	0.00	kWh/year
	Total supplied energy	E_{si}	964,030.00	kWh/year
Real energies	Natural supplied energy	$E_{sr,n}$	754,377.76	kWh/year
	Shaft supplied energy	$E_{sr,p}$	694,371.78	kWh/year
	Total supplied energy	E_{sr}	1,448,749.54	kWh/year
Efficiencies	Ideal efficiency of the system	η_{ai}	0.43	-
	Real efficiency of the system	η_{ar}	0.28	-

3.1.4. Diagnostic conclusions

As a first overview of a pressurized water network, the diagnostic is more than appropriate and will allow the user to draw some conclusions. The more one knows the network beforehand, the better the results will be understood, if not, further assessment is needed to interpret the results. In the beginning, Teruel’s layout would lead to think that its different elevations would result in a poor network efficiency however, the three networks present ideal efficiencies below 50%. This is a major issue that the diagnostic is evidencing, the vast amount of topographic energy in condemning the efficiency.

Another interesting aspect that comes out of the comparison of the different networks is the supplied energy balance between natural and shaft energy. Sagunto’s network clearly reflects the difference between the two layouts, Sagunto city centre is more elevated than Port Sagunt and that is why natural energy plays a more important role in Port Sagunt than in Sagunto. This, in relative terms indicates that improvements in the energy supply (the pumps) in Sagunto will have a greater impact than in Port Sagunt, whereas in absolute terms is the other way around given the total amount of energy handled in the latter network. Teruel’s natural supply is also very important conforming almost half of the energy supply.

And what is common to the three networks in the margin between the ideal efficiency and real efficiency what indicates energy losses that are not depicted in the analysis so, in order to determine with more accuracy where these losses are, more work is needed.

3.2. Analysis. Water audit

When the diagnostic step has been carried out, the next station is to analyse the network itself. In the unusual case where the diagnostic is very favourable, the analysis of the network will be done. The system works good, there are neither significant energy losses nor water losses. As it has already been mentioned, the diagnostic tool is limited in terms of network complexity, the more complex the network is, the less reliable the diagnostic is. For that reason, a very favourable diagnostic is only recommended to be trusted in case the studied system is simple enough to have it under control with the basic input data. Normally, in studies like this one where time and resources are deployed to carry out this kind of assessments, the water audit will be done as well, since it is basic in water systems. Generally, a water audit is usually done in order to evaluate the volumetric efficiency of the network. They are common and they should also be frequent although it is not always the case. When water is lost, the problem is double. On the one hand the water itself is wasted, needless to say the current problems with finding and managing water resources and the environmental impacts associated, and secondly, in pressurized water systems, the energy is embedded in the water, so its lost implies an energy lost as well and therefore coming back again to the environmental issues we face nowadays. In gravitational or non-pressurized water systems, water also has embedded energy, though it is generally not accounted in monetary terms since it is free, however, it should not be this way since water is a scarce resource and it does not matter whether if it costs money, it should be well administrated. Furthermore, in the long term it will have economic impacts because the infrastructures will become undersized and investments are then needed.

A low level of leakage in a network is also important in terms of healthy. Leakages imply by definition a flow of water out of the water carrier, but under certain working operation conditions, cracks are liable to become a disease-causing pathogen source. Furthermore, systems with high leakage indexes are difficult to manage when there is a high demand, and sometimes they cannot even handle it and a supply cut is the only solution (El País 2015).

In order to carry out a water audit it is first necessary to depict the classification that has been more or less established in water conventions. A current water balance follows the classification below in Figure 3-5:

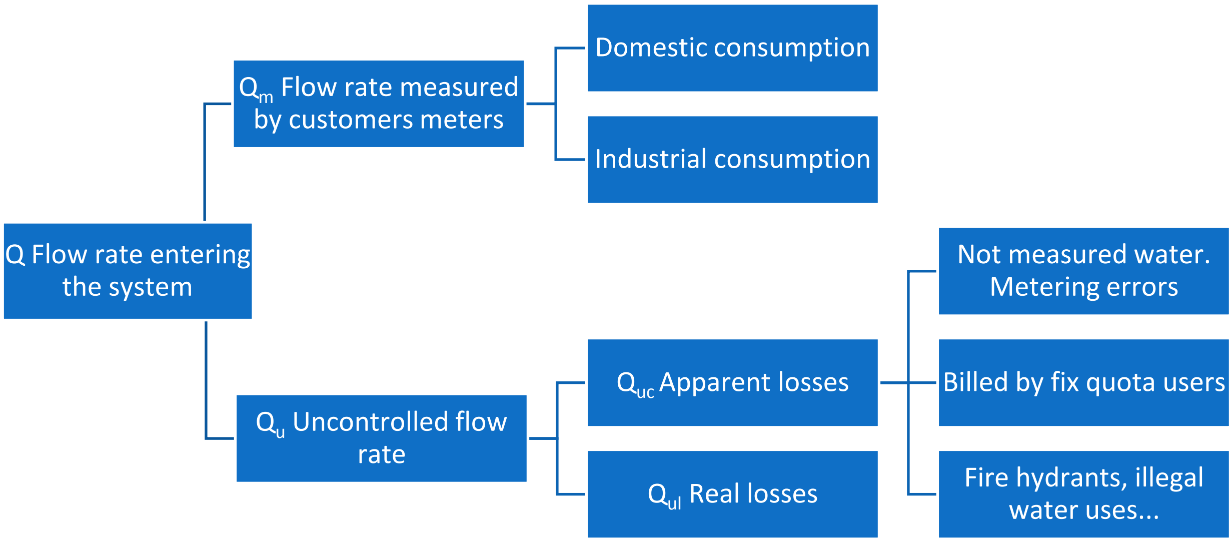


Figure 3-5. Water balance classification.

The International Water Association (IWA) distinguishes between revenue water and non-revenue water, therefore, it classifies water depending on whether it is billed authorised consumption or not (American Water Works Association 2012). But in terms of water balance, the classification that matters is depicted in Figure 3-5. The total flow rate Q, usually measured in m^3/year is accounted in every water entry to the system. Then, basically water is broken down into what is measured and what is not measured. Domestic, industrial, official or any customer with a water meter at its input point of the network will account for what is known as billed or registered flow rate (Q_m). And the rest of the water that is not measured is known as uncontrolled flow rate (Q_u). But not all the water that has not been measured is lost. It is distinguished between apparent losses or uncontrolled consumed (Q_{uc}) and real losses or uncontrolled leakage (Q_{ul}). Apparent losses include any public consumption such as hospitals, irrigation of public parks, fire hydrants but also any illegal consumption that is not registered, water robbery, water meters' bypasses… and finally metring errors, something that is not unusual since a very low flow rate may not activate the flowrate meter or just the metering is incorrect. Water companies should be aware of their metering technology in order to take this into account. Normally, metering accuracies with a 5% error is considered very high (Almandoz et al. 2005), but a bad or lack of maintenance will make this value increase.

With this general outline, hydraulic balances can be carried out easily. As easy as water meters exist on the key points of the network. That is, on the inlets and at each consumption node. This sounds obvious but there are cases where the inlet metering is not place right at the exit of the water source but for example at the exit of the water treatment plant (WTP). If the water company just controls or regulates water consumption downstream, then it is ok. However, it is very common that some of the consumption nodes are upstream of the WTP right after the water source, what means that the control volume is not fully under control. Additionally, depending on the distance from the main water source and the way water is carried to the WTP (which is usually pumped water), and important amount of water and energy might be lost just here.

The global volumetric efficiency (η_s) of a water network is calculated as follows:

$$\eta_s = \frac{Q_m}{Q} \quad (8)$$

However, if the water demand raises in the upcoming years, or, in general terms, if water demand increases in any water supply, the volumetric efficiency shows a clear lack of relativity, since the volumetric efficiency will improve. It is for that reason that some relative indicators must be analysed as well to be able to compare the water efficiency of a supply, (Cabrera et al. 1999).

Some useful operational water losses indicators are:

1. Water losses per time (m^3/h): Total water losses expressed in terms of time.
2. Water losses per connection (m^3/connection/year): Total water losses expressed in terms of annual volume per service connection. This is adequate for urban distribution systems such as these case studies.
3. Water losses per mains length (m^3/km/day): Total water losses expressed in terms of daily volume lost per mains length. This indicator is adequate for bulk supply and low service connection density distribution systems.
4. Infrastructure leakage index (ILI): It is an ambitious indicator that tries to include all risk factor in a water system such as number of connections, length of the network and time plus the length of the connections and the service pressure.

According to the results of the previous volumetric efficiency, the network can be tagged as (Cabrera et al. 1999):

Table 3-4. Rating of a water network according to the volumetric efficiency.

Range	Grade
$\eta_s > 0.9$	Excellent
$0.9 > \eta_s > 0.8$	Very good
$0.8 > \eta_s > 0.7$	Good
$0.7 > \eta_s > 0.6$	Regular
$0.6 > \eta_s > 0.5$	Bad
$0.5 > \eta_s$	Not acceptable

The complementary of the volumetric efficiency is the uncontrolled water which can be either consumed uncontrolled water or actual water losses.

Dividing Q_u into Q_{uc} and Q_{ul} is not an easy task. The local water company should gather the necessary information for such a task, but in most of the cases this information is not available. There are different methods to assess uncontrolled water and assign it to the real leakage group or apparent losses. Action plans are completely different for a network where almost all the water is leaking through its piping system than those where water is actually being consumed but not registered properly. For the former, renewal piping plans if the network is very old might be one solution. This is usually expensive. Or a leakage detection campaign could be another solution. However, for the latter, the guidelines are focused on determining if water is being actually stolen or consumed in public places by the installation of water meters, etc.

The water consumption pattern for these two groups is very different as well. Apparent losses, unsurprisingly, follow regular water consumption patterns. During the day water is usually consumed (for example in a city hall), whereas in night hours the consumption decreases. For stolen water the pattern is even clearer. A family having a bypass in their input water meter will have the exact same behaviour as regular people.

On the other hand, real water losses behave in a different way. During the day, the water demand is higher and therefore, pressure in the network is usually lower. Since water leaks depend on pressure, during the night, when water consumption is lower and the pressure in the network higher, water leaks increase.

One methodology makes use of the above principle described to determine the water losses of a network and differentiate them from apparent losses. This is known as the "Minimum night flow" (MNF). There are complete studies demonstrating the application of such methodology (Alkasseh et al. 2013), where more detailed information can be found for this topic.

Another methodology described in (Almandoz et al. 2005) acts differently. From Q_u being the total amount of water not registered, x is the percentage of Q_u that really leaks the system (Q_{ul}). X varies from [0 – 1] being x=0 no leakage in the system and $Q_u = Q_{uc}$ and x=1 all the water is leaking and $Q_u = Q_{ul}$. If the water evolution through the day is known and how much water at each hour of the day is consumed, then it is possible to calculate the average consumption as well as the standard deviation. The methodology consists of iterating x from 0 to 1 in steps of 0.1 for example until the standard deviation coincides with original one. This will give rise to a percentage of leaked water and the complementary consumed water.

Leakage assessment plays a very important role in water network analyses and the amount of energy lost through leaks is often underestimate. But the very first step is to know that the system is indeed losing water in order to be able to act.

3.2.1. Leakage calculation tool for mathematical models. ITAFugas

As it has already been mention about the importance of water loss determination, the next step is to introduce the leakages to our model. ITAFugas is a tool developed at the ITA, that eases the process of assigning leakages to Epanet water models. The objective of ITAFugas is to determine the emitter coefficients that are used in Epanet to simulate leaks. These emitters are introduced in each consumption node in Epanet so that it adds an extra water demand that is pressure dependent simulating a leak.

It will be described briefly how the program works since it is a key step to a proper update of the mathematical model.

Leaks are pressure dependent and the main advantage of ITAFugas is the fact that it can assign a different emitter for each node depending on the pressure of the node. The steps to follow with the software are the followings:

1. The registered volume is read from the initial Epanet model file .inp.
2. The injected volume (Q) or the volumetric efficiency are introduced manually. This leaves an uncontrolled volume to be assigned in leaks and apparent consumption.

3. The program calculates the percentage of leaked water and apparent losses by two different ways. First one is an estimate of the uncontrolled volume. The user introduces the percentage of real leakages and apparent losses (better if it is known) from the uncontrolled volume which is known. The other way the program calculates this percentage is through the X method explained in the previous point.
4. The emitter exponent allows to take into account the increment of the leakage area with the pressure, but it will be left constant to 1.1

The uncontrolled volume associated to consumption (Q_{uc}) is directly added to the demand of the nodes and with the leaked volume, the emitters are calculated.

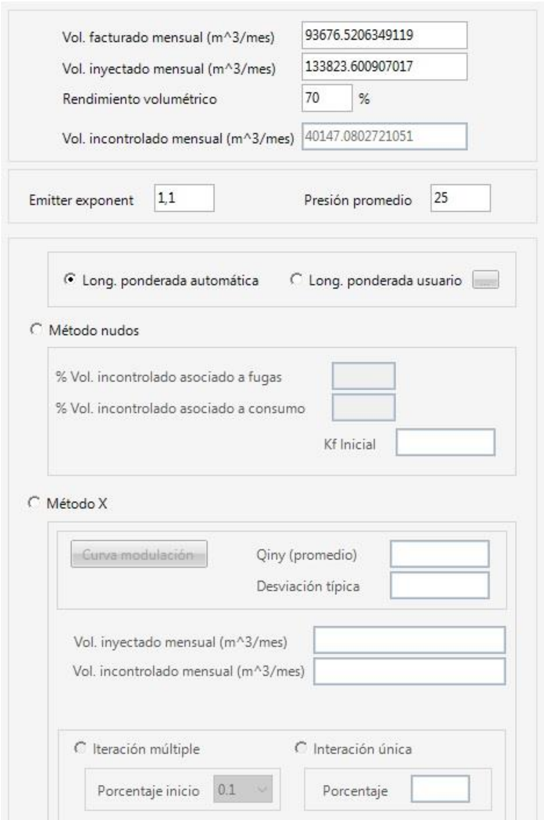


Figure 3-6. ITAFugas screenshot. General setting for the calculation of the emitter coefficients

The leaked flow is calculated as follows:

$$Q_{ul} = K \cdot P^{\Upsilon} \qquad (9)$$

With

$K = Emitter\ coefficient$

$P = Pressure$

$\Upsilon = Emitter\ exponent$

The program calculates a first emitter exponent and the way it has to assign the leaked volume in the form of emitter is to distribute the volume according to weighted length of the pipes. To each node it is associated the water volume of all the weighted lengths of each pipe intersecting the node. Then, the program verifies that the sum of all demands plus the leaked volume of each node coincides with the total injected volume. If not, it changes the emitter coefficient until it converges to the solution. In order to make it converge, the mean pressure introduced in the program should be of the same order to that of the model.

The outcome of the program is an .inp file readable by Epanet with the node's demands upgraded and all the emitters of each node introduced modelling leakage.

3.2.2. Water audit results of Teruel

In order to carry out a proper water audit it is obviously necessary the appropriate water meters at the inlet point as already mentioned before. For Teruel, this is not the case.

Teruel is divided in two main parts as described in 2.1, the bulk supply and the retail water supply. The main water source is the reservoir of Arquillo. Water is pumped to the header tank and from it, it is sent to the water treatment plant after supplying water to the small town of El Campillo and the industrial state of Teruel.

In parallel, the well of Caudé supplies water to the towns of Caudé and Concud and the rest arrives to the WTP as well.

The problem arrives when the first water meter is placed at the outlet of the WTP, that is, at the beginning of the retail water supply, or the supply to the city of Teruel itself. There are neither water meters at the exit of the reservoir or header tank nor at the exit of the well of Caudé.

Since there is not reliable data about the total injected water, the work will be based on the retail water supply data and the water audit will exclude the following points:

- El Campillo
- Caudé
- Concud
- Industrial State
- Any water loss from the bulk supply to the WTP

The procedure to calculate the injected volume from the water treatment plant is the following in the basis of the available information.

In the WTP there was a water meter installed that was known to measure inaccurately. With an unknown measurement error. In mid-July 2016, a new water meter well calibrated is installed. Therefore, the following data is available. Uncertain water measurements from January 2016 until July 2016 and much more accurate measurements from August 2016 to late October 2016 (the latest date when data has been collected). Since there are two complete months (August and September) with measurements of the two water meters, it is possible to determine an approximate error of the old meter with the new measurements.

1. The error of the old meter is calculated for the two months.
2. The mean error is calculated.

3. The mean error is applied to the data from January to July in order to correct the previous data available.
4. For the months of August and October, the data from the new meter is taken.
5. For November and December, the same datum as October from the new meter is taken (Considering the exact amount of days of each month). This is possible since the water consumption for these two months is historically almost the same as October. In fact, the water consumption of Teruel throughout the year is pretty steady except for the months of summer when irrigation makes water consumption increase.

In Table 3-5 and Table 3-6 it can be seen the data registered by the water meters, both the old one and the new one. Although there is a value for the daily mean in the new water meter in the month of October, there is not available data for the whole month. For that reason, only the months of August and September have been used to estimate the error of the old water meter.

In Table 3-7 the absolute value for the error is calculated as well as the relative value of it. With the average value of the error, it has been applied to the previous months registered with the old meter in order to correct the measurements shown in Table 3-8

Table 3-5. Water measurements from the old water meter in m³

Month	Days	Daily mean. Water sent to network. (m³)	Total monthly volume. Water sent to network (m³) (M1)
1	31	8,530	264,460
2	28	8,765	254,190
3	31	8,396	260,300
4	30	9,042	271,260
5	31	9,830	304,760
6	30	11,293	338,790
7	31	11,667	361,681
8	31	11,353	351,972
9	30	10,608	318,250
10	31	8,521	
11	30		
12	31		

Table 3-6. Water measurements from the new water meter in m³

Month	Days	Daily mean. Water sent to network (m³)	Total monthly volume. Water sent to network (m³) (M2)
1	31		
2	28		
3	31		
4	30		
5	31		
6	30		
7	31		
8	31	10,623	329,317
9	30	9,861	295,832
10	31	8,003	248,093
11	30		240,090
12	31		248,093

Table 3-7. Calculation of the error made in the months of August and September.

Month	Error (M2-M1)	%Error
8	22,655	0.068793898
9	22,418	0.075779496

Table 3-8. Corrected injected volumes (m³)

Month	Monthly corrected volume (m^3)	Daily corrected volume (m^3)
1	246,632	7,956
2	237,054	8,466
3	242,752	7,831
4	252,973	8,432
5	284,215	9,168
6	315,951	10,532
7	337,299	10,881
8	329,317	10,623
9	295,832	9,861
10	248,093	8,003
11	240,090	8003
12	248,093	8003
Total	3,278,301	

Finally, the water audit results are shown in Table 3-9. The total injected volume is an estimate calculated based on data until end October 2016, however, the registered volume is taken from the whole year of 2015. There is not necessity for an estimate since this value is actual water consumption from the users and it is supposed to be correct it one omits the measurement errors of the water meters at the consumption nodes.

Table 3-9. Water audit results of Teruel

Annual injected volume from WTP in 2016 (Q)	3,278,301 m^3
Registered volume in 2015 (Q_m)	2,236,974 m^3
Volumetric efficiency of the retail water supply	**68.24%**

According to Table 3-4, the supply of Teruel is considered regular. It is almost 70% which does not sound very bad, but in absolute values it is 1 million cubic meters of water being lost every year in the supply, almost 1/3. It is a big amount of water that should try to be recovered with further actions.

It has been mentioned that a water audit has to come before the energy audit and one of the reasons is to assess whether if the water consumption distribution is well spread across the network. This work is not only a hydric assessment but a whole methodology for studying water networks. By this, it is meant that water audits are usually done by themselves and in some water networks a lot of resources are devoted for water audits. In the case of this project, the methodology allows for an accurate detection of where energy losses are taking place but a proper hydric audit is never done. So, in the eventual case that energy loss has its main origin in water leakage, further actions to ameliorate this aspect are supposed to be done.

On the other hand, with the available data collected, it is worthy a preliminary assessment on water distribution among the network as follows:

For the case of Teruel, 2,236,974 cubic meters of water are billed by the water company. According to the last report of the National Statistics Institute (Instituto Nacional de Estadística 2016), the average consumption of domestic water is 132 litres per person and day. In the case of Teruel, considering the billed water volume and the population in 2015, the average consumption is 172 per person and day. It seems high but there are two important points to consider about Teruel. The first one will be seen in the next sections when the energy audit is done, but in Teruel the mean pressure of the network is high, and this is usually translated in a higher consumption of water. The second aspect to be considered is that certain irrigation consumptions are also included in the billed water volume. The latter, more than the former reason, explains to some extend the high water consumption. But in the event of need for more information regarding water consumption among the users of the network, additional studies must be carried out.

Regarding the use of the indicators described in 3.2, only indicators 1 and 3 can be obtained with the available information:

1. Water losses per time: 118.9 m^3/h
2. Water losses per mains length: 15.42 $m^3/km/day$ (185 km of network)

A general guideline for the second indicator is a value lower than 9.5 $m^3/km/day$ (Cabrera 2005).

3.2.3. Water audit results of Sagunto

Contrary to what happened in Teruel, in Sagunto information is much more accurate and available. If Figure 2-6 is observed, water meters are all over the network. The main ones lay right after the pumping station in the water treatment plant. There is metering for the industrial states, Sagunto city centre, Port Sagunt and another to L'Almardà (a coastal location that will not be studied). In addition, there are flowmeters after the main water tanks just before entering the control volume of study. For that reason, the injected water volume to the network is already known, and there is no need for estimation, which is not recommended.

Table 3-10 shows the data of the water injected (Q) and consumed (Q_m) by the users in the year of 2015, since it is the last complete year with available information.

According to Table 3-4, the volumetric efficiency is generally good, even very good for the industrial state zone. However, the absolute values reveal that 2 million cubic meters are lost throughout the year. It will be seen later on which are the main causes for such lost. Although the general picture that such hydric balance reveals is that there are important losses, a more specific zoom is necessary in order to be able to actually act.

From the results, it is easy to see the greatest impact that Port Sagunt has, and therefore, improvements in this part will result in much more water savings in general. As it has already been explained, leakage has basically two main impacts: the first one is obviously the water loss itself, but the second one is related with embedded energy. Those 2 million cubic meters of water have been previously pumped and the energy cost has an economic effect on the managing company.

Table 3-10. Water audit results of Sagunto in 2015

	Sagunto CC + NP	Port Sagunt + Canet	Parc Sagunt + Camí La Mar	Total
Injected (Q) (m^3)	1.639.549	4.694.670	407.449	6.741.668
Registered (Q_m) (m^3)	1.139.731	3.504.762	350.061	4.994.554
Volumetric efficiency (η_s)	69,51%	74,65%	85,92%	74,08%

In the case of Sagunto, the water consumption is well differentiated by the different areas. For assessing the water consumption distribution, the industrial state area will not be taken into account. So the billed volume in Sagunto is equal to 4,644,493 cubic meters for the year 2015. According to the population registered for that year (64,944 inhabitants), gives an average consumption of 195 litres per person and day. It seems that the results are nonsense due to such high value. In some extend that is true, it is difficult to conclude the domestic water consumption out of the total billed volume since there is no data about the consumers. However, according to (Instituto Nacional de Estadística 2016), the Valencian Community has the highest domestic water consumption of all Spain with 166 litres per person and day, so the result shows, in some extend, this tendency with respect to the rest of Spain.

Regarding the indicators, as it has been done with Teruel:

1. Water losses per time: 57 m^3/h in Sagunto CC + NP
1. Water losses per time: 135 m^3/h in Port Sagunt
2. Water losses per mains length: 16.8 $m^3/km/day$ in Sagunto CC + NP (81.4 km of network)
2. Water losses per mains length: 21.7 $m^3/km/day$ in Port Sagunt (154 km of network)

Still, bad results if the reference mentioned before is taken, but also the evidence that the first indicator does not tell too much since the hours of a year are always the same (8760 h/year) and as the leaked volume increases, this indicator will worsen.

3.2.4. Water audit conclusions

Water has most part of the energy supplied to a pressurized water network embedded in itself. Therefore, losing this water during its way to the end user means a waste of energy as well. This is one of the reasons why the water audit is needed first instead of the energy audit. If one is losing the water it does not matter how efficient you are when supplying the energy and how efficient your pumps are because the energy is being lost anyway.

The volumetric efficiencies for both networks are similar, although Sagunto is slightly better, in absolute values, 1,747,114 m^3 are lost in Sagunto against 1,041,327 m^3 in Teruel. This comparison is obviously not fair if the total population is not taken into account. But this has already been done in the previous two sections.

One the first conclusions obtained is the similarity between the volumetric efficiencies of Teruel and Sagunto CC + NP. And one explanation for this might be that both of them are governed by terrain irregularities such as differences in elevation, whereas Port Sagunt is mostly plain. The higher nodes leave the lower ones with an excess of topographical energy that is translated in more water leaks, due to this overpressure. This does not explain however, how such a flat area as Port Sagunt has still a considerable water loss of more than 1 million cubic meters. So, this explanation is left for the next energy analysis.

The water demand distribution is not easy to assess with such little information, although a first introduction has been given for both supplies thanks to the INE figures. The consumption per capita in Teruel is lower than in Sagunto but both are still high. The explanation is not easy when no information about the final consumers is not provided. Whether if it is a public agency, if irrigation is included in the registered volume or if fire hoses have been used more than usual this year (just a mere example) may influence the results. For such case, and as mentioned several times before, water audit of a network is usually done by itself, employing much more resources to dig deeper for the information requested before.

Nevertheless, thanks to the results already obtained, it can be said that Teruel has a higher leakage index possibly due to its wider extension of ground with elevation differences than Sagunto. Furthermore, although the first indicator does not tell too much in absolute values, the second one that has been calculated already says that being Port Sagunt the longest network, it has the poorest result (between Teruel, Sagunto CC + NP and Port Sagunt) so there is clearly a lack of explanation that is missing just with this water audit.

3.3. Mathematical model update

The fact of addressing this point after the water audit might not be correct. The mathematical model is the base for the whole assessment of a water network through this methodology. It is needed for the energy audit that will be explained in the next section, that, in the end, it is the most important step for the study. However, this process does not come after the water audit (therefore why it might be wrong to place it here) but in parallel. Both processes can be done at the same time and they even should. There is no need for having the ultimate model before proceeding with the water audit and the other way around. In fact, the water audit might be useful for updating the model with regards to the water consumptions introduced in the model. If there is enough information about the different consumptions in the network, then it is the perfect moment to update the model with the right water demands. That is why this parallel procedure might be helpful.

Updating the mathematical model is crucial as already mentioned for different reasons. The other option is directly to create a mathematical if it does not exist. For this work, both mathematical models were already available, but the accuracy of them was far from being optimal.

One of the main aspects that has been changed are the water demands. This has to do with the water audit and it is referred to updating the registered water volume to its latest figure. In this case, the year 2016 fir the case of Teruel and 2015 for the case of Sagunto. It is important that time frames are in concordance since the pumping data and water demands are those for the year 2016 and 2015 respectively so the models must be updated accordingly.

Another important aspect to highlight is the revision of the pipelines. In a metropolitan water network is it usual to do reparations, maintenance or new pipe derivations. This implies closing valves and changing the water flow distribution. So, an important amount of time has been devoted to checking all the differences in the pipeline since the last mathematical model, especially for Teruel. Furthermore, it is important to know how water is flowing from the source to the distribution points in order to visualize if a pipe is being overused (and therefore friction losses having a big impact) or to be able to modelled a possible network division into DMAs (District Metring Areas), as it will be seen in next sections.

So as to continue with the different steps of the methodology, the mathematical model is needed. Although it has not been explained the many changes done to the existing mathematical model of Teruel, it has been one of the most important works done throughout the working period. There is a lot of bibliography on modelling with Epanet water networks, big networks as well as minor ones. In fact, this work is based on two existing case studies with their respective mathematical models already done. However, if the model is not well calibrated in terms of pumping (where energy is supplied), network pipelines open or closed (for water flow distribution) and water demands (for energy consumption) as the main aspects, the energy audit in the next step will never be possible. Additionally, the introduction of the leakage is very important as well by means of the previously described methods to be able to assess leakage, obviously.

3.4. Analysis. Energy audit

The energy audit is the third step in Figure 3-1. After the water audit, the energy audit is already possible. It makes no sense to do it the other way around since firstly, one needs to know if the network is demanding the required water. Although normally the energy audit will come right after the water audit in a seamless process, if the results of the former offer straight forward actions, they could be applied before entering in the energy audit. The point of carrying out the energy assessment after is to verify where or what do all the water losses imply in terms of energy, as well as any other energy loss introduced by any other elements. However, water will be the main source of energy inefficiencies.

In the end, everything could be translated to energy terms, even environmentally talking, CO_2 is measured per kWh produced. In the diagnostic section, an introduction to the energy terms in a pressurized water supply network has already been done. The concepts here are no different. The variation lays under fact that the energy audit will be much more exhaustive and will give more detailed information, mainly about the energy losses.

Water systems usually have different sources of losses, but in general, the main ones are grouped almost always in the same blocs.

The energy flow to be analysed in a pressurized network does not vary and it can be seen more graphically in Table 3-11. It is represented the real energy inserted into the system by means of the two main sources; natural or gravitational energy and shaft or pumping energy. From the table, it is easy to identify the efficiencies of the system depending on which indicator one wants to represent.

Furthermore, percentages are also easy to be illustrated and give the user a rapid understanding of the main issues of the network. For example, the energy loss in friction can be shown as a percentage of the energy losses but also as a function of the total input energy. They might represent most of the energy losses, but it these are low, then they should not be considered to have a big impact on the network.

The energy audit focuses on the detection of energy losses. It is probably the most important part of the whole assessment due to the information that comes out of it. Although the audit gives data about the useful energy, the main objective is to keep track of the inefficiencies and correct them. If the minimum required energy of the system is not adequate (too high for example), it is to the analyst to inform or regulate the situation. In addition, this step is key because it will let one know about the status of the network, how much energy is wasted and what is more important, where it is being wasted. It might be the case that improvements to the network are not possible to be implemented after the evaluation, due to monetary reasons or because the cost-benefit analyses are not favourable, for example. But in any case, the information provided will allow to plan mid and long-term measures if the sort term ones are not to be applied yet.

Table 3-11. Energy distribution in a pressurized water supply system

<table>
<tr><td rowspan="6">Input energy
(E_{sr})</td><td rowspan="3">Natural energy
E_N</td><td rowspan="2">Energy delivered to users
E_u</td><td>Minimum required energy
E_{uo}</td></tr>
<tr><td>Topographic energy
E_{tr}</td></tr>
<tr><td rowspan="4">Energy losses
E_r</td><td>Energy loss in leakage
E_{rl}</td></tr>
<tr><td rowspan="3">Shaft energy
E_p</td><td>Energy loss in pumping
E_{rp}</td></tr>
<tr><td>Energy loss in friction
E_{rf}</td></tr>
<tr><td>Other energy losses
E_{ro}</td></tr>
</table>

After having proceeded with the energy audit, one should be able to identify all the different energies depicted in the table above. The percentage of energy delivered by natural means or through pumping systems will depend on the network layout and requirements.

If most of the energy is introduced without the need of pumps, it can be assumed that the energy is "free". And by free it is understood that there is no electric cost for pumping the water or for pressurizing the network. However, "free" water supply infrastructure does not mean that network is properly functioning. There will not be pumping losses, obviously, but nothing assures that the energy lost through water leaks is low enough or the friction losses are under acceptable limits. If this is the case, however free the energy is, the network will eventually not withstand upgrades or increasing demands. This will imply much greater efforts for adapting the network to these possible future needs. Whereas being aware of the limitations of the network leaves a huge margin for planning.

On the other hand, each kWh consumed by the pumping stations of the network or the pressure system will be reflected in the electric bill of the company and localizing the losses of the network will have much more tangible results if reduced afterwards.

How is energy audit performed?

The basic concept is to apply the energy equation to a control volume where hydric and energetic fluxes go through the limiting surface. The objective is to determine the energy fluxes, for that reason, it is necessary to get the hydraulic balance solved and have the mathematical model well calibrated. The control volume can be defined in many ways, so that the election matches the best possible way the desired studied area. Elements staying out of the control volume will contribute with energy fluxes, whereas inner elements will be able to store energy (tanks) or dissipate it. Pumps are usually external elements and they supply shaft energy to the control volume, and the exits of the system are found in the water supply connections and water leaks.

Some of the energies depicted in Table 3-11 have already been explained in section 3.1, mainly the energy delivered to the user. Now, a closer attention will be given to rest of them, being the energy losses the main focus.

Supplied Energies

The total energy supplied to the system can come from two sources:

- Natural energy (E_N):

$$E_N(t) = \gamma \cdot \sum_{i}^{n_N} \left(\sum_{k} Q_{Ni}(t_k) \cdot H_{Ni}(t_k) \cdot \Delta t_k \right) \tag{10}$$

Where γ is the specific weight of water, $Q_{Ni}(t_k)$ is the flowrate (m^3/s) supplied by the reservoir at instant t_k, $H_{Ni}(t_k)$ is the piezometric head (m.w.c) at instant (t_k) and Δt_k is the time frame chosen. In Epanet, the simulation takes place in an extended period. If the head of the reservoirs do not change through the simulation, the expression can be simplified:

$$E_N(t) = \gamma \cdot \sum_{i}^{n_N} \forall_{Ni} \cdot H_{Ni} \tag{11}$$

Where $\forall_{Ni}$ is the total volume supplied by reservoir i for the whole analysis and H_{Ni} is the piezometric head (m) for each reservoir.

- Shaft energy (E_p):

$$E_P(t_p) = \gamma \cdot \sum_{\mathrm{t_k=0}}^{\mathrm{t_k=t_p}} \left(\sum_{\mathrm{i=1}}^{n_p} \left(\frac{q_{Pi}(t_k) \cdot h_{Pi}(t_k)}{\eta_{pi}(t_k)} \right) \right) \cdot \Delta t_k \qquad (12)$$

Where q_{Pi} is the flowrate (m^3/s) through the pump at instant (t_k), h_{Pi} is the head (m) supplied by the pump, η_{pi} is the hydraulic efficiency for the working point at instant (t_k) and Δt_k is the time interval considered in the simulation. The calculations will be done for the total number of pumps $(\mathrm{n_p})$ that will contribute with work to the system.

This is real energy consumed by the pump stations. Although initially pumps could be considered to be out of the control volume and therefore their efficiencies could be excluded from the supplied energies, the efficiency of the pumps is a crucial parameter in water systems' energy assessments and it must be included.

Energy losses

- Energy loss through leakage (E_{rl}):

Leaks, as usually when modelling a network, are concentrated at the nodes and their value depend on pressure. They represent an energy outlet. The energy delivered to the users is also output energy, but from the point of view of the energy audit, it is a lost equal to:

$$E_{rl}(t) = \gamma \cdot \sum_{k} \left(\sum_{i=1}^{n} q_{li}(t_k) \cdot H_i(t_k) \right) \cdot \Delta t_k \qquad (13)$$

Where n is number of nodes with leakage in the distribution network, q_{li} is the leaked flow (m^3/s) through the adjacent pipes of the node i at instant (t_k), H_i is the piezometric head (m) at instant (t_k) at the node where the q_{li} leak is.

- Energy loss in pumping (E_{rp}):

$$E_{rp}(t_p) = \gamma \cdot \sum_{\mathrm{t_k=0}}^{\mathrm{t_k=t_p}} \left(\sum_{\mathrm{i=1}}^{n_p} \left(q_{Pi}(t_k) \cdot h_{Pi}(t_k) \cdot \left(\frac{1}{\eta_{pi}(t_k)} - 1 \right) \right) \right) \cdot \Delta t_k \qquad (14)$$

Only the hydraulic efficiency of the pump is considered. Similar to eq. (12), q_{Pi} and h_{Pi} are the flowrate (m^3/s) and head (m) (working point of the pump) at instant (t_k). It is easy to see from the expression that the energy loss is the difference between the energy consumed by an ideal pump with efficiency $\eta_{pi} = 1$ and the actual pump with the corresponding efficiency η_{pi}.

- Energy loss in friction (E_{rf}):

The energy loss due to the friction of water with the pipe walls of the system is:

$$E_{rf}(t) = \gamma \cdot \sum_{k} \left(\sum_{j=1}^{n} \left(q_{uj}(t_k) + q_{lj}(t_k) \right) \cdot \Delta h_j(t_k) \right) \cdot \Delta t_k \qquad (15)$$

Where j is the number of pipes of the distribution network, Δh_j is the head loss (m) of the line j at instant (t_k). The head loss is the difference of piezometric head between the initial node and final node of the pipe. The head loss is calculated according to the introduced equation (Darcy – Weisbach equation, Hazen – Williams equation or Chezy – Manning formula) and the roughness defined for each pipe that allows the calculation of the friction coefficient. q_{uj} is the flowrate necessary for the user and q_{lj} is the flow that will be loss through leakage. The total flowrate through the pipe will the sum of both.

From the expression above it can be observed that leakages imply an extra flow that will induce an additional head loss since before leaving the network through a crack, for example, it has circulated along the pipe.

- Other energy losses (E_{ro}):

In this classification, it is included everything that is not friction, pumping or leakage, obviously. There are a lot of different elements in a water network that may cause an energy loss, normally in the form of head loss. In pumping stations, the different elbows or bends, filters, diameter reducers, valves…, and through the piping network mainly valves, water chambers and joints are the main factors for head loss. All those are considered minor losses, and there are equations for calculating the head loss they introduce. However, the extension for this energy audit is limited, and they will not be taken into account. Except for the valves. They are a very common element and in this case, they will be depicted in the audit. Finally, another important source of energy loss are break pressure tanks. If energized water arrives to a unpressurized tank, it will lose all the added energy. However, in Epanet, this kind of energy loss is usually simulated with throttle control valves that introduce localized head losses.

3.4.1. Energy audit calculation tool. ITAEnergy

In order to make energy audit possible, ITAEnergy is the utilized software. ITAEnergy has been developed in the Grupo de Ingeniería y Tecnología del Agua (ITA), at the UPV. Although other supporting software has been used and described in this document, this is the most important tool used for this work along with Epanet. The main objective of ITAEnergy is to carry out an energy audit of a pressurized water supply system with the mathematical model of Epanet.

The programme will determine which is the final use of the energy introduced in the system through the reservoirs and pumping stations. Determining if the energy is useful energy, in the form of required energy or overpressures, or it is wasted energy trough leakage, friction or pumping inefficiencies, as it has all been described already in the previous sections.

The concepts and considerations on which the software is based are developed in the scientific paper of (Cabrera et al. 2010), and some of the concepts about topographic energy and ideal efficiency in (Cabrera et al. 2015).

To obtain the results of the energy audit, only the mathematical model of the network in Epanet is required (.inp file). The software does not analyse the system but just uses the results of the simulation that Epanet provides to make energy calculations. Therefore, the validity of the results of the energy audit are subjected to the validity of the model. If the model does not function properly, incorrect working points for the pumps, negative pressures, closed valves…, results will be equally incorrect. It is to the user to previously validate the model and thus, the importance of this task.

Since the different energies and losses have already been explained, in this section just the considerations that the software makes in its calculations will be described.

- Natural energy:
  - If more than one reservoir supplies the network, the energy will be shown for each of the reservoirs. The higher one will normally supply more energy although it also depends on how much water it is extracted from them.

- Shaf energy
  - The most important aspect to calculate the shaft energy that ITAEnergy will consider is the definition of a pump curve in Epanet. This curve should be as real as possible. Sometimes it is not easy to get the real curve, even more if the pump is old and the impeller has been rectified in several times.
  - The working point considered for eq. (14) is taken from the curve previously defined. And ITAEnergy will pick the corresponding working point at each instant time defined in the simulation.
  - The last essential aspect for ITAEnergy to calculate the energy is the definition of the efficiency curve of the pump. At each instant, the working point considered has an associated efficiency that allows the software to compare it with an ideal pump of efficiency equal to 1.
  - If more than one pump is used in the pumping station or in different points of the network, the energies will be broken down into each pump in addition to their working time, number of hours that the pump has worked through the simulation.
  - There is no possibility with this software to calculate the inefficiency of the pump station since only the hydraulic efficiency of the pump is considered and there is no option (in Epanet) to introduce an overall efficiency of the station.

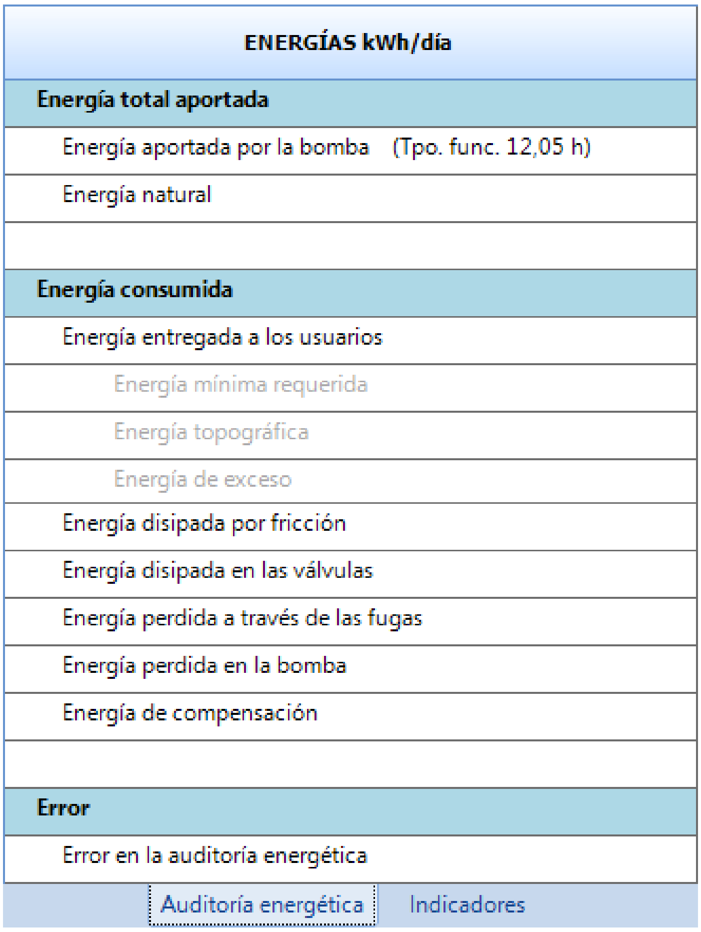
- Leakage
  - Leakage is calculated with the emitters previously introduced in the model with ITAFugas. If there are no emitters in the nodes, there will not be water leaks and therefore, no energy loss through leakage.
  - The energy loss in leakage that ITAEnergy calculates is a function of the flowrate that leaks and the piezometric head of the node at each instant, and the flowrate that leaks is function of the above-mentioned emitter and the pressure, therefore, pressure plays a crucial role in the energy loss in leakage.
  - The most important consideration or assumption related with leaks is about the emitter. In order to calculate the emitters, ITAFugas has been used, as explained in 3.2.1. The estimation of real water losses (Q_{ul}) and apparent losses (Q_{uc}) influences the results. A common estimate is to assign 75% - 25% or 80% - 20% to real losses and apparent losses respectively. The higher the percentage associated to real losses, the

greater the energy loss through leakage will be. And obviously, the more accurate the estimate is, the better.

- Friction
  - Since the software carries out the audit with the complete water balance, it is not possible to distinguish between the friction loss due to the extra flowrate of leakage and the flowrate demanded by the user. But it is possible to know how much friction energy is due to this extra flowrate (leakage) and how much is "inevitable" due to the necessary water for the users (water demand). In order to do so, a simulation of the network without emitters is needed, so that the difference will be associated to leaks.

- Other
  - Other considerations to take into account are the valve losses. Whenever energy is dissipated in a valve, it will be accounted in this aspect. Valves always introduce friction losses and thus dissipate energy. However, whenever a break pressure tank exists in the network, all the energy loss in this break pressure tank will be simulated through a loss in a valve.

Next, in Figure 3-7, it can be seen a screenshot of the software energy results in ITAEnergy according to all the theoretical aspects and considerations described above and made by the programme.



ENERGÍAS kWh/día
Energía total aportada
Energía aportada por la bomba (Tpo. func. 12,05 h)
Energía natural
Energía consumida
Energía entregada a los usuarios
Energía mínima requerida
Energía topográfica
Energía de exceso
Energía disipada por fricción
Energía disipada en las válvulas
Energía perdida a través de las fugas
Energía perdida en la bomba
Energía de compensación
Error
Error en la auditoría energética

Figure 3-7. ITAEnergy audit results table with the different energies calculated. Screenshot from the software

3.4.2. Case study energy audit results. Teruel

After describing the whole process of auditing in terms of energy, the understanding of the results of the case studies is easier. As done with the diagnostic and the water audit, herein are presented the results for the energy audit of Teruel.

Two energy audits will be done in terms of network disaggregation. First, a global audit with the whole network, bulk and retail supply. This one includes the whole pumping and therefore, the main energy consumption. Secondly, an energy audit of the retail water supply only will be done. Here, no energy consumption coming from the pumping is assessed, however, a closer look to the main network can be taken.

Global energy audit

The main assumptions that have been made to perform the audit are the following two:

1. 30 m.w.c as service pressure. In Teruel there is no minimum service pressure stablished by the local authorities. Therefore, in the consumption nodes, a minimum pressure of 30 meters must be assured. It could have been even lower, but regarding the high pressure levels already existing in the network, a greater decrease in pressure would be too noticeable.
2. The percentage associated to real water losses and apparent losses has been 75 – 25% respectively. For the not registered volume there are no further data regarding what this relation could be. Although this might seem a random estimate, there has been an agreement between the people in charge of the network and the water company managers.

The results herein presented are in kWh per month.

Table 3-12. Results of the energy audit of the network of Teruel. Global results

Input Energy	175,614	kWh	%
Shaft energy	72,681	kWh	41.4
Natural energy	102,933	kWh	58.61

Total energy consumed	177,172	kWh	%
Energy delivered to users	79,365	kWh	44.8
Minimum required energy	62,121	kWh	78.27
Topographic energy	17,835	kWh	22.47
Excess energy	0	kWh	0
Energy loss in friction	18,920	kWh	10.68
Energy dissipated in valves	31,902	kWh	18.01
Energy loss in leakage	23,130	kWh	13.06
Energy loss in pumping	23,505	kWh	13.27
Compensation energy	349	kWh	0.2
Error in the audit	-0.89%		

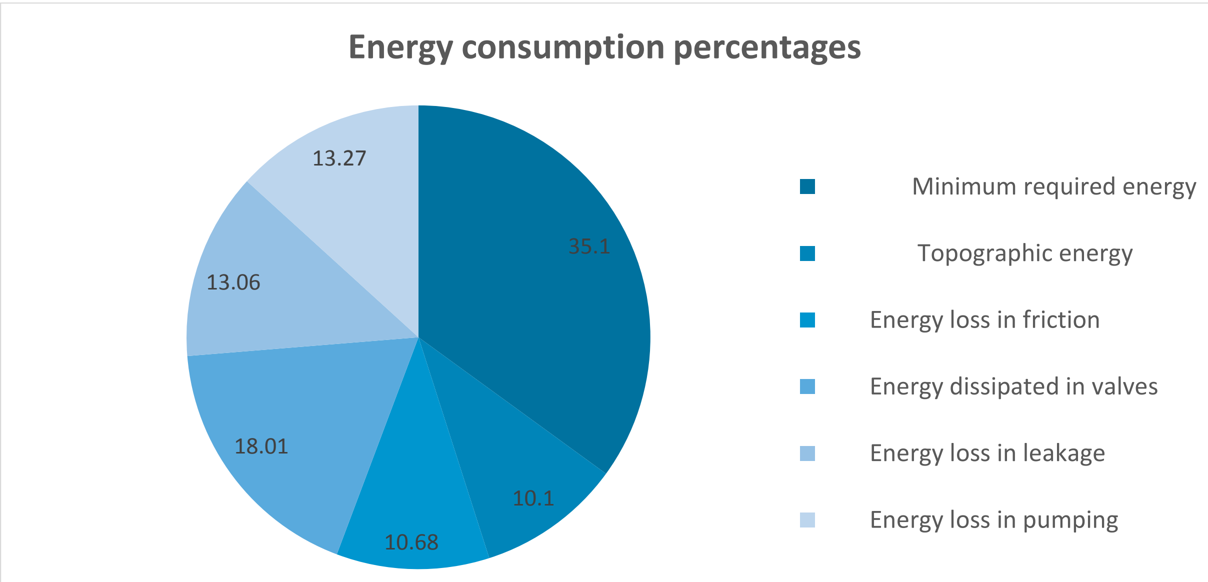


Figure 3-8. Energy consumption distribution in percentages. Global audit

Thanks to this global analysis, it can be seen the importance of the pumping in the network. In the case of the network of Teruel, it means an energy supply of shaft and natural energy of 40 – 60 approximately. This means that the main reservoir has also enough height to be considered of importance so that not all the water must be pumped. In addition to this, the system is supplying 55% more of the energy that the users are receiving. There are therefore, a lot of losses.

It is of importance to mention that there is a considerable percentage of energy loss in valves and it is necessary to explain why. In the mathematical model, there are throttle control valves that regulate the filling of the tanks. In order to regulate the incoming flowrate of a tank to that of the real situation, a throttle valve is placed, what reduces the flowrate but it also introduces head losses. In such way, there are too much head losses reflected in valve losses when in reality are being lost in break pressure end tanks or, in some cases, as friction losses through the pipe.

The other part of the energy is wasted in the form of pumping inefficiencies and water leaks, that can be seen in more detail afterwards.

Retail supply energy audit

With the aim of knowing the state of the network of Teruel itself (city centre), this audit is done. More specifically, the main reservoirs and pump stations are deleted. The tank "Viejo" has been converted into a reservoir in order to be able to simulate. The height of the reservoir that has been taken is the mean water level of the tank throughout the year 2016, whose value is known. This level varies within 0.5 meters, so the deviation is not significant.

The results are depicted in Table 3-13:

Table 3-13. Results of the energy audit of the network of Teruel. Retail supply results

Input energy	99,643	kWh	%
Shaft energy	2,590	kWh	2.6
Natural energy	97,053	kWh	97.4

Total energy consumed	90,007	kWh	%
Energy delivered to users	59,512	kWh	66.12
Minimum required energy	44,626	kWh	74.99
Topographic energy	15,153	kWh	25.46
Excess energy	0	kWh	0
Energy loss in friction	3,993	kWh	4.44
Energy dissipated in valves	10,781	kWh	11.98
Energy loss in leakage	15,348	kWh	17.05
Energy loss in pumping	358	kWh	0.4
Compensation energy	14	kWh	0.01
Error in the audit	9.67%		

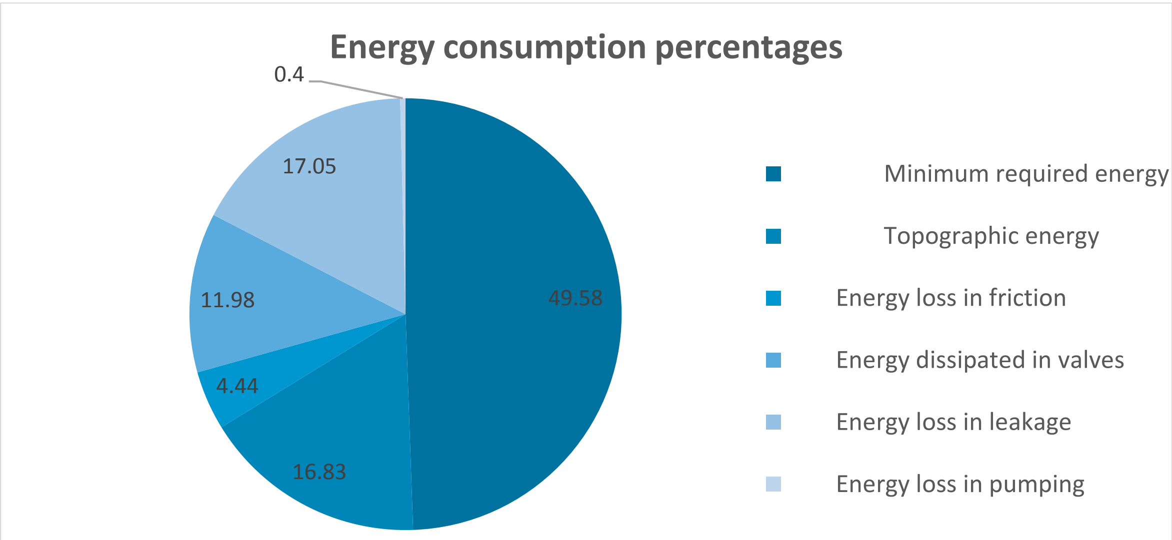


Figure 3-9. Energy consumption distribution in percentages. Retail supply audit

The analysis in Table 3-13 gives a more detailed information about what happens in the main network. It must be remarked that although the shaft energy is not included, it has an important impact on energy distribution. Three main conclusions come out of the results:

1. The energy delivered to users in the retail supply represents a 66% of the energy consumed, whereas including the bulk supply, this value drops to a 44%. This means that the bulk supply is less energy efficient than the retail supply. This gives already an important information of the energy loss distribution.
2. The network of Teruel receives an extra of 50% of energy. Topographic energy (which is technically delivered to users in the form of overpressure), friction energy, valve energy and leakage energy count 45,275 kWh per month out of 44,626 kWh really necessary.
3. Topographic energy is liable to be reduced. If the overpressures are reduced, then leaks decrease and operational failures usually go down as well.
4. Leakage is the other main source of energy waste. As mentioned, if acted over point 3, then leaks also decrease due to the relationship between both. Additionally, extra water maybe be saved and therefore, it should not be pumped with its additional economic cost of pumping extra water. On the other hand, it is possible to carry out the audit with a different approach to assess leakage. Firstly, the one already done (including pumping as well), and secondly, another without water losses (without water leaks). This way it is possible to evaluate the additional energy that the extra water produces, as well as the extra friction losses that the extra water produces when circulating through the pipes, etc. If energy loss in leakage is important enough, it may be worth it to do such audit. Furthermore, the software allows this task without too much additional effort.

Leakage assessment

As mentioned above, another audit without leakage will be carried out. To do so, the emitters of the mathematical model have been removed. Results are depicted in Table 3-15. Although the initial audit has been done in Table 3-12, the service pressure has been changed to 25 m.w.c in order to see how it is reflected for this analysis. So Table 3-14, is the equivalent to Table 3-12 but with service pressure set to 25 m.w.c.

Table 3-14. Energy audit with leakage

Input energy	175,614	kWh
Shaft energy	72,681	kWh
Natural energy	102,933	kWh

Total energy consumed	177,172	kWh
Energy delivered to users	79,365	kWh
Minimum required energy	58,563	kWh
Topographic energy	21,208	kWh
Excess energy	0	kWh
Energy loss in friction	18,920	kWh
Energy dissipated in valves	31,902	kWh
Energy loss in leakage	23,130	kWh
Energy loss in pumping	23,505	kWh
Compensation energy	349	kWh

Table 3-15. Energy audit without leakage

Input energy	144,041	kWh
Shaft energy	56,768	kWh
Natural energy	87,273	kWh

Total energy consumed	139,719	kWh
Energy delivered to users	80,366	kWh
Minimum required energy	58,563	kWh
Topographic energy	22,204	kWh
Excess energy	0	kWh
Energy loss in friction	13,198	kWh
Energy dissipated in valves	27,698	kWh
Energy loss in leakage	0	kWh
Energy loss in pumping	18,127	kWh
Compensation energy	328	kWh

In order to evaluate the results, Table 3-14 and Table 3-15 should be compared. The time window is a month. The effect of changing the service pressure is reflected in the topographic energy and minimum required energy. The lower the service pressure, the higher the topographic energy. If less energy has to be delivered to the users, the rest is supplied in the form of overpressure (topographic energy). This can be observed by comparing Table 3-12 and Table 3-14. The rest remains similar.

In the comparison, it has been erased the energy percentages, since it is not the same amount of energy so only absolute values can be considered.

- Leakage imply 31,573 kWh more of energy supplied to the network per month. It is a 22% extra energy introduced in the system due to leakage.
- Of all the added energy due to leakage, 15,913 kWh are supplied by the pumping system. It is 28% more than the energy they would consumed without leakage. And the problem with this energy is that it costs money in terms of the electric bill.

- The additional flowrate through the pipes imply a 43% more of energy loss in friction, that is 5,722 kWh loss in the pipes due to leakage.
- Obviously, all the energy embedded in the leak is lost completely. This means 23,130 kWh per month. There is no way to eliminate leakage at 100%, but there is an important margin for improvement in this point.
- In pumping, 5,378 kWh are lost due to the inefficiencies of the pumps due to the extra energy necessary to be pumped for the extra flowrate.

The impact of leakage is high, a part from the economic saving that not pumping an additional water volume implies, it must be considered the water that can be saved and the lower CO_2 emissions due to the lower energetic expense. According to the IDAE (Institute for Energy Diversification and Saving) (MINETUR 2014), with a mean CO_2 emission factor and with a multiannual projection that makes the factor independent from the climatological conditions, but just dependent on the production method (0.357kgCO_2/kWh final), leakage imply 135 tons of CO_2 per year in Teruel.

3.4.3. Case study energy audit results. Sagunto

The energy audits in Sagunto will be separated in two as previously done with the diagnostic and water audit. The point in doing it like this is that both supply elements (pumps) are completely differentiated and modelling is relatively easy to separate them. Additionally, the city centres are in different locations and even elevations are different. This last aspect is important since it will be possible to study different strategies according to the overpressure present in each area.

In Sagunto there is no local legislation that regulates the service pressure, as it happened in Teruel. For the audits 20 m.w.c has been set as the service pressure. Elevations in Sagunto are pretty even and, although 20 m.w.c might be just, it is an acceptable value. There is no specific criterion for choosing this value. If there are not too many high buildings, or specific water end uses that need extra pressure, twenty meters is enough. Usually tall buildings have their own pressure system to boost water up to the last floors, however, up to the second or third floor should be provided by the public water network. In conclusion, although up to 30 m.w.c is within an acceptable service pressure value, 20 meters has been the agreed value for carrying out the audits. Tuning this value obviously has an impact on the minimum required energy for the users.

In Table 3-16, the results for the energy audit of Port Sagunt and Industrial State are displayed. The results are expressed in kWh per month and the state of the network is that of 2015 with water demands updated to 2015.

Table 3-16. Energy audit of Port Sagunt + IS

Input energy	96,793	kWh	%
Shaft energy (Working time 375.00 h) (12.5h/day)	37,099	kWh	38.3
Natural energy	59,694	kWh	61.7

Total energy consumed	95,546	kWh	%
Energy delivered to users	48,732	kWh	51.0
Minimum required energy	33,811	kWh	69.4
Topographic energy	14,921	kWh	30.6
Excess energy	0	kWh	0.0
Energy loss in friction	6,682	kWh	7.2
Energy dissipated in valves	19,160	kWh	20.1
Energy loss in leakage	14,895	kWh	15.6
Energy loss in pumping	5,854	kWh	6.1
Compensation energy	223	kWh	0.2

Error in the audit	*1.28 %*

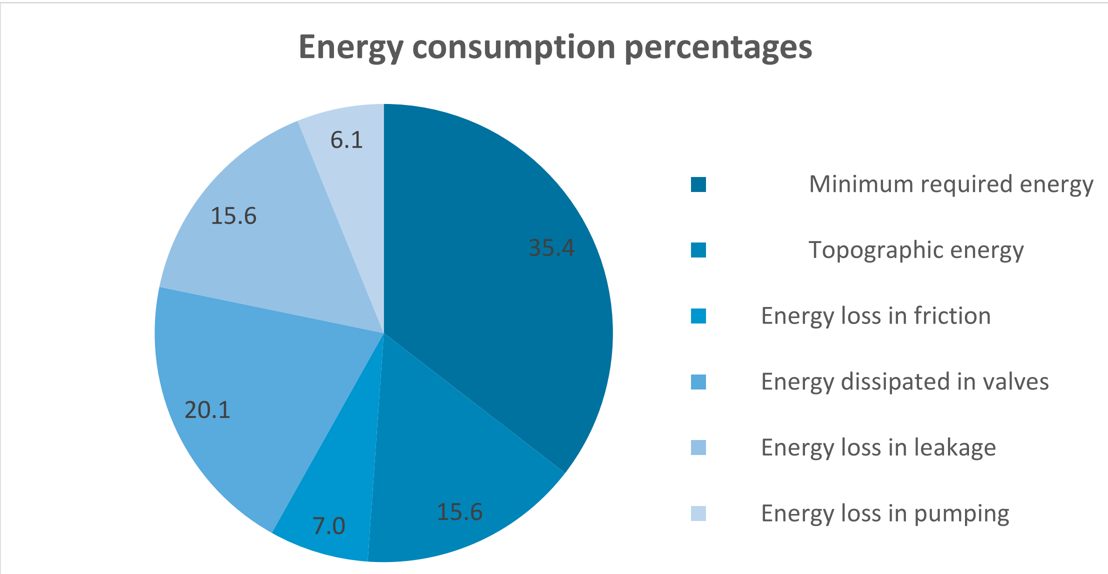


Figure 3-10. Energy consumption distribution in percentage. Port Sagunt + IS

So, from Table 3-16 and Figure 3-10, the first conclusions come. Firstly, it can be seen that Port Sagunt receives more energy from natural means than from pumping (60 – 40 approximately). This means that the only reservoir, which is the water treatment plant from where the network starts, has a considerable elevation with respect to the network's elevation.

The system is consuming almost 50% more energy than needed by users since required energy plus topographic energy is 51% that users actually receive, whereas the rest is lost.

The energy losses are basically due to two main causes. 20% of the energy delivered is lost in valves and almost 16% in leakage. The first cause is easily explained thanks to the system layout. There is a break pressure tank right after the main distribution tank so that pressures are not too high in the whole network of Port Sagunt. By taking a closer look to the layout of the network:

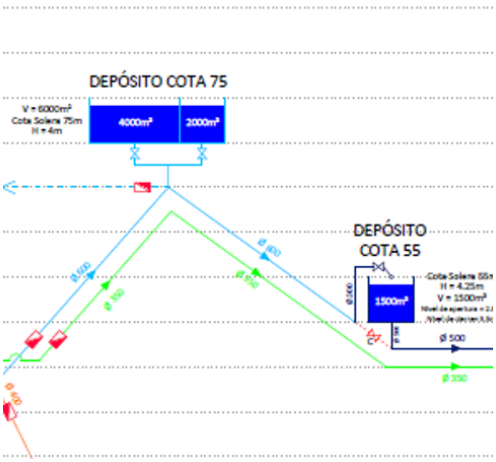


Figure 3-11. Detail of the break pressure tank in Port Sagunt

It can be seen that after the tank of elevation 75 meters, 20 meters of water column are directly dissipated in the tank of elevation 55 meters. The way to simulate this break pressure lost is with a valve at the inlet of the tank, thus, the high energy loss in valves given in the audit results.

For the energy loss in leakage, although 20 meters are already gone before entering the network of Port Sagunt, pressure is still high enough to produce considerable water losses though leakage. The mean elevation of Port Sagunt is 11 metres whereas the break pressure tank is located at 55 metres. This explains the still high pressures in the network. For that reason, further actions that will be commented later are needed to reduce this effect.

Next, and similarly to Port Sagunt, the initial energy audit has been done to Sagunto city centre and North Palancia.

Table 3-17. Energy audit results of Sagunto CC + NP

Input energy	38,166	kWh	%
Shaft energy (Working time 269.00 h) (9h/day)	30,008	kWh	78.63
Natural energy	8,158	kWh	21.37
Total energy consumed	38,468	kWh	%
Energy delivered to users	20,103	kWh	52.26
Minimum required energy	9,793	kWh	48.71
Topographic energy	10,312	kWh	51.29
Excess energy	0	kWh	0
Energy loss in friction	3,903	kWh	10.15
Energy dissipated in valves	0	kWh	0
Energy loss in leakage	9,270	kWh	24.1
Energy loss in pumping	5,177	kWh	13.46
Compensation energy	16	kWh	0.04
Error in the audit	-0.79%		

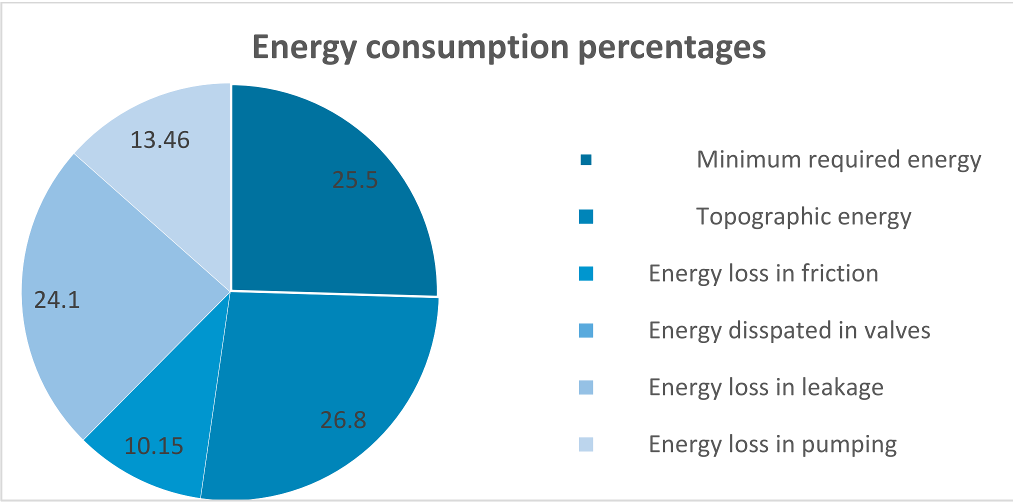


Figure 3-12. Energy consumption distribution in percentage. Sagunto CC + NP

The results of Sagunto CC let one observe that shaft energy has a much more significant impact than natural energy (almost 80 – 20%). For that reason, a saving in the supplied energy will imply more economic consequences than Port Sagunt, a part from the energetic and environmental consequences. This is because of the elevation of Sagunto centre, which is higher than that of Port Sagunt.

Regarding the losses, the network is again near to the 50% of extra energy supplied than the required by the system. Leakage represents a 24% of the total energy supplied so measures to reduce the pressure will help to reduce leakage as well. And here, it can be seen that pumping losses acquire a higher importance (13%), as shaft energy does. The reason for this is the higher elevation of Sagunto, so that more pumping is needed since the natural energy cannot be varied.

It can be observed as well a high weight of the topographic energy. Betterments will be directed to make this topographic energy drop, and therefore overpressures and leakage will also decrease.

Since in this part of the network there are no break pressure tanks, there are no energy losses in valves.

3.4.4. Energy audit conclusions

The energy loss distribution is much clearer now after the energy audit has been performed and it clarifies some of the water audit unknowns. Although the general results are more or less similar, the situation in Teruel is slightly worse than in Sagunto with 55% of the total energy lost against 49 and 48 % in Port Sagunt and Sagunto respectively.

One of the most important points about energy distribution is the related with the topographic energy in all scenarios. Teruel shows a 16% of topographic energy in the retail supply, Port Sagunt almost a 16% as well and Sagunto goes up to almost 27%. This explain in all the cases another important issue that these three networks are facing, the water losses. This overpressure related to the topographic energy increases water leak proportionally to the pressure. Teruel is historically thought to be much more irregular (geographically talking) than a flatter area such as Sagunto, however, in Sagunto CC, where the heights are less plain than Port Sagunt, this situation reveals much more relevant than in Teruel. This reveals that a better distribution of the pressure in Sagunto CC is likely to have important consequences in terms of energy, although it is obviously important as well to manage the topographic energies in Teruel and Port Sagunt.

Teruel has poorer pumping efficiency than Sagunto and, although it makes little sense to face and compare both efficiencies between them, these results show what one can see then on site, older pumping equipment a more disperse what leads to questioning how to handle future pumping extensions.

The topologies of both networks are pretty different and one of the main discrepancies lays on the amount of end tanks found in the network of Teruel that Sagunto does not have. Although this is not reflected directly in the audit, it is indeed reflected in the energy dissipated through the valves in Teruel which is an important 13% of energy and zero in Sagunto, whereas the break pressure tank in Port Sagunt launches the value to 20%. The network layout will be analysed forward with more detail in the next section, but it is important to remark how quickly these results highlight this issue where an important amount of energy is lost, it might be inevitable or not, but the lost is there and it should be tackled.

Comparing the values of the energy results between them may not seem the most reasonable option since each network has its topology and its problematic, however, it is convenient to remark that both audits provide useful information that, with appropriate exploring actions, can lead to important reductions of energy inputs.

4. EXPLORING ACTIONS

The networks have already been assessed. Thanks to the energy audits, one is able to distinguish the major energy losses of a pressurized water network and act accordingly. Thanks to the methodology and the use of the described tools, the whole process explained is totally free. All the tools are free software or tools under development that will be soon available for any user. There has not yet been any investment and the only cost is the devoted time spent in assessing and modelling the network. It is obviously not a free procedure due to this employed resource but it can be assumed that a company will have employees that will be equally paid if dedicating time to anything else.

The point of this section is that, once the network is much better known, betterments can be made so that the energy efficiency of the system is improved. In this case, and following the procedures already described, these improvements can similarly be modelled and assessed through ITAEnergy in order to see the impact that they might have, and so it will be proceeded.

A series of improvements will be analysed and passed through the energy audit software for the networks of Teruel and Sagunto.

Obviously, the final aim for this is to go onsite and act on the networks. Measures that are liable to affect the operating conditions of the system are basically classified into two different classes:

- Operational measures:

They do not imply an economic investment on the network but just changing the operating conditions of the system. These actions have normally an immediate impact since they usually consist of changing the working point of a pump to its BEP (Best Efficient Point) (if for example it is working in a low efficient point according to its curve), or they may imply the redirection of the flow by closing existing valves if there is an overused pipe. The more operational actions to be carried out, the less the economic impact. However, sometimes it may not be sufficient.

- Structural measures:

These actions are supported by an economic investment. Therefore, they need to be well analysed in order to weight the cost-benefit impacts. It may require the change of the whole pump if changing the working point does not provide a reasonable efficiency. It is also very common to carry out pipe replacements in order to avoid or repair major leaks or changing the layout are also a good example of structural measures. Recovering or reducing the topographic energy is a very frequent measure to apply. The use of PATs to recover this energy or the use of PRVs to reduce it.

4.1. Exploring actions in the network of Teruel

Improvement 1: Network division into District Metering Areas (DMA)

One of the projects with greatest impact on the network of Teruel would the division of the network into different sectors or district areas. It already exists a preliminary draft project from 2015 ("Proyecto de sectorización de la red de Teruel") for stablishing DMAs in the network, but it is still far from being executed. In any case, this draft version has been followed in order to evaluate the energy efficiency impact through the methodology explained in this project. With the guidance of the draft, the implementation of the DMAs has been modelled in Epanet with 14 different sectors dividing the network of Teruel. It is not the aim of this work to develop on how to proceed in the DMA technology for a water network or even carry out the division of this network into the DMAs. It is for that reason that the existing draft has been used. But the fact of modelling the different sectors in the software will allow to see the feasibility of it, and what is more important, the energetic impact.

In principle, just the fact of dividing the network into different metering areas should not imply a reduction of the energy demand of the system. The main reason for dividing a network is to delimit different areas of a network so that information is more easily available and reduced to a specific DMA, with more detail and so, problems are easier to find. However, DMA philosophy usually forces water to flow along certain pipes so that it enters a sector or DMA through the desired points (in order to install water meters for the sector). The tendency is to use the main pipes to enter a sector and then flow towards the smaller pipes within the sector to supply water to users (as it is expected from a ramified system). If the network is not divided and pipes are all interconnected among them, it might be possible that water enters a main zone through a small pipe, therefore introducing too much friction losses. For that reason, although the main idea for DMA principles is the above-mentioned, it may occur that friction losses can drop after the division process is performed. All this will be seen once the energy audit is done.

In Figure 4-1, the different sectors considered for the whole network are shown.

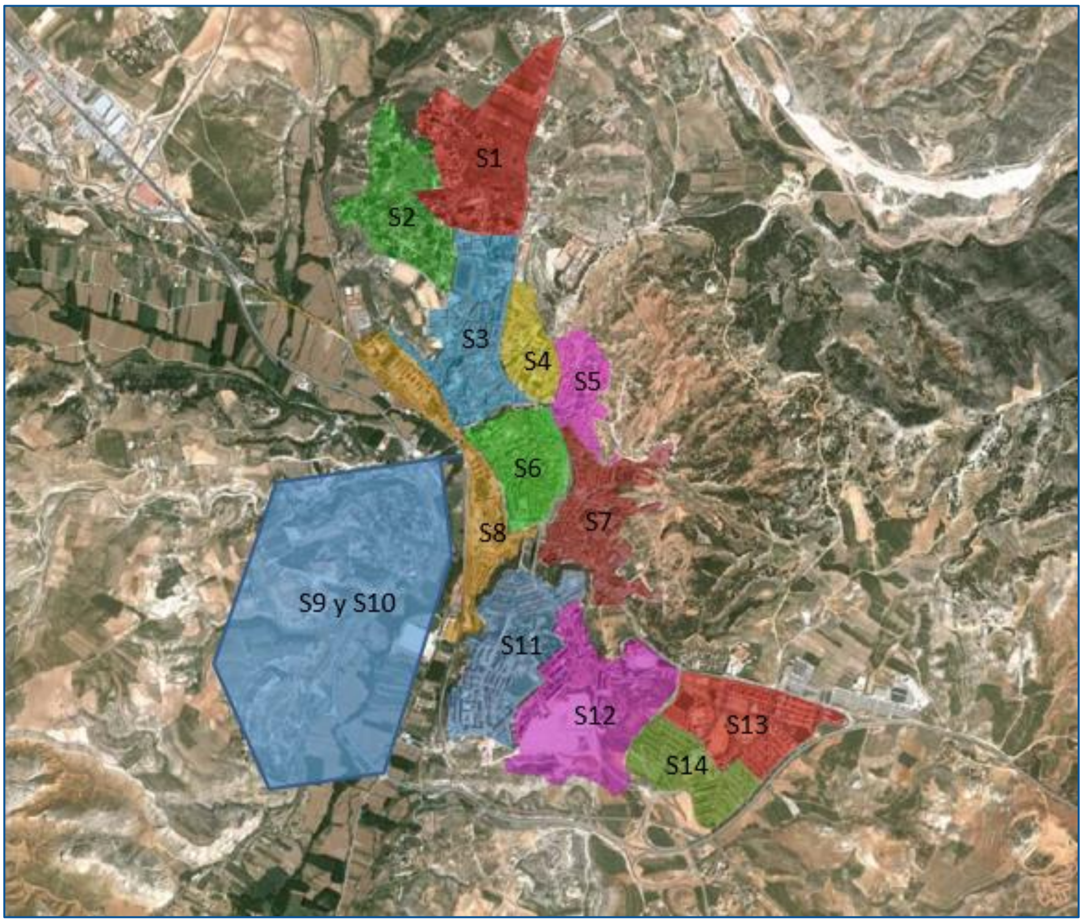


Figure 4-1. Sectors of the network of Teruel

Thanks to Epanet it has been possible to model the network division of the draft project. However, it has not been possible to create the 14 different DMAs that were initially designed. This has a positive side in some extend, the software has proven the feasibility of the different sectors and it has shown that some of them are not possible the way they were designed due to the network layout. With the model analysis, a deliverable is created with enough detail so that the maximum correspondence with the initial draft can be achieved. In that case, the creation of the DMAs is easier. However, it is not the aim of this document to develop such detailed analysis.

Improvement 2: Installation of pressure reducing valves at the entrance of some sectors

One of the advantages of performing a network division is the enhancement for pressure mapping management. By installing PRVs at the entrance of a DMA, the pressure is regulated downstream (just in the sector if it is isolated or in the sectors downstream if they are interconnected).

Thanks to the modelling it is easy to create a pressure map in order to have an idea of where the greatest pressures are. The idea is to reduce the main overpressures of the network.

In Figure 4-2, the pressure map of Teruel can be seen. This is how the pressure is distributed in the least favourable hour, that is, when the flow rate is maximum and pressures are low. The lowest pressure (service pressure) must be assure at the worst hour in terms of operation conditions.

It must be noted that the network shown is without the bulk supply, and a reservoir is simulating this bulk supply as explained in 3.4.2 “Retail supply energy audit”.

It can be observed that the central part of the network concentrates the higher pressures reaching values of more than 65 m.w.c. However, it is not only the central part of the network but a generalised high pressure is governing the system. This explains the high topographic energy as well as the high losses in friction and valves as explained in the energy audits.

The mean pressure is 49 m.w.c. for the whole network, value that is considered too high for an urban water distribution network.

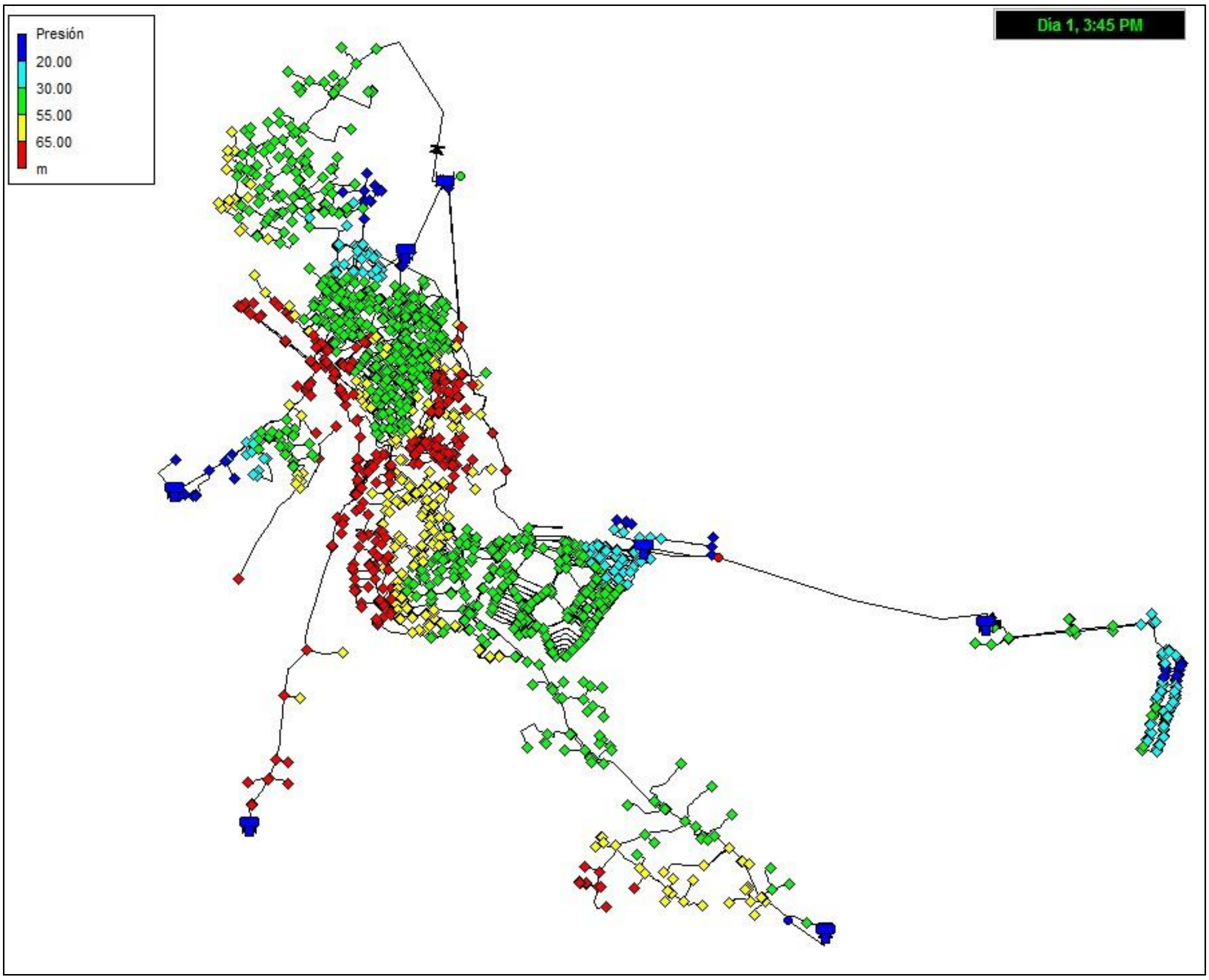


Figure 4-2. Pressure map of Teruel at the least favourable hour

After observing the pressure map the following PRVs have been installed:

- PRV at entrance of DMA 11
    - Pressure set point: 30 m.w.c. the whole day
- PRV at entrance of DMA 7
    - Pressure set point: 25 m.w.c. the whole day

- PRV at entrance of DMA 6
    - Pressure set point: 30 m.w.c. the whole day
- PRV at entrance of DMA 13 and 14
    - Pressure set point: 25 m.w.c. the whole day

It can be seen in Figure 4-3 the approximate situation of the pressure reducing valves modelled in the network. As it has already been explained, not all the sectors have been achieved in the model. For that reason, DMA 8 does not have a PRV, although it might be thought as a candidate to lower the pressures in that zone. This leaves some margin of improvement on how to better isolate this area in order to be able to reduce the pressure without affecting other areas.

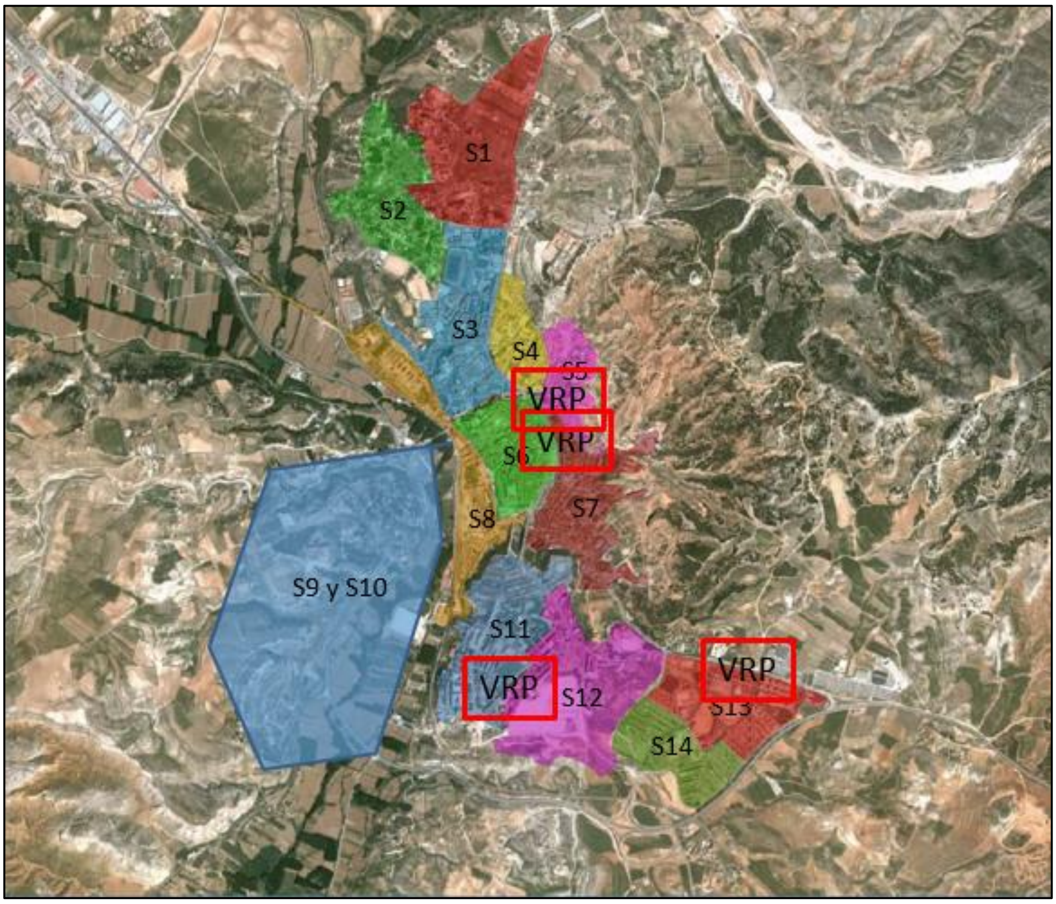


Figure 4-3. Location of the PRVs in the network of Teruel

4.1.1. Results

After having modelled the different improvements of the network, if Figure 3-1 is taken back, the next step is to repeat the auditing process so that one is able to see the how the energy efficiency of the network has improved. The process will be repeated with ITAEnergy. The positive side is that it is possible to get a water audit as well with the software.

After improvements 1 and 2, the average network pressure has dropped up to 38 m.w.c. That represents a 23% reduction from the initial 49 m.w.c. If Figure 4-4 is observed, most of the network pressure is still above the 30 m.w.c. established as the service pressure in the energy audit analysis (see section 3.4.2 for more information). However, there are some points where the pressure is still high.

The main results of the different measures are reflected in Table 4-1. In the first part of the table there is the water balance and in the second part there is the energy audit. The initial state column reflects the results without changes on the network whereas the other columns show the different improvements. Results are expressed in kWh per month and they follow the same structure as the tables with the audit results in the previous sections.

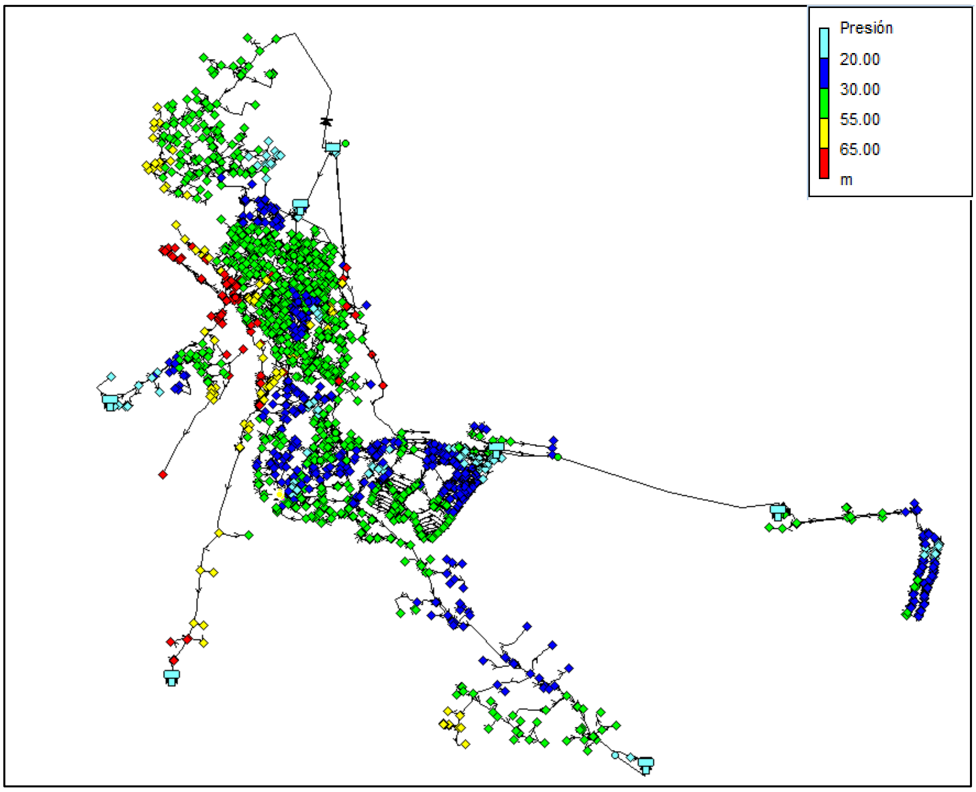


Figure 4-4. Pressure map of the network of Teruel after the improvements

Table 4-1. Results of the energy and water audits with ITAEnergy after the improvements in the network of Teruel

TERUEL BULK AND RETAIL SUPPLY. PUMPING INCLUDED						
Water balance	**Initial state**		**Improvement 1**		**Improvement 2**	
Input volume (m^3/month)	387444		369066		359726	
Consumed volume (m^3/month)	261142		261114		261114	
Leakage volume (m^3/month)	73402		67195		61273	
Energy audit	**kWh/mth**	**%**	**kWh/mth**	**%**	**kWh/mth**	**%**
Shaft energy (Ep)	86532	42.8	82235	42.6	79750	42.5
Natural energy (En)	115903	57.3	110650	57.4	107980	57.5
Energy delivered to users	79010	39	74139	38	70258	37
Minimum required energy	62121	79	62116	84	62116	88
Topographic energy	17544	22	12714	17	9348	13
Excess energy	0	0	0	0	0	0
Energy loss in friction	21193	11	20630	11	19865	11
Energy dissipated in valves	34617	17	39178	20	42739	23
Energy loss in leakage	22827	11	20326	11	18186	10
Energy loss in pumping	27947	14	26478	14	25660	14
Compensation energy	16025	7.92	11944	6.19	11288	6.01
INPUT ENERGY	**201621**	**100**	**192695**	**100**	**187995**	**100**

As mentioned, in Table 4-1 it can be found the results of the energy audit for the initial state of the network and the two improvements made described in 4.1. However, in order to visualize the effects of the betterments, in Table 4-2 there are the results in terms of savings, that is, the difference between the energy consumption in the initial state and the improvements. Results are shown in absolute values -Initial state minus Improvement 1 for improvement 1 and improvement 1 minus improvement 2 for improvement 2- and in percentage, what shows the percentage of energy saved. The percentage for improvement 1 is referred to the initial state whereas the percentage for improvement 2 is with respect to improvement 1 (I1) and initial state (IS).

Table 4-2. Audit results of Teruel. Savings

SAVINGS						
Water	Initial state	Improvement 1		Improvement 2		
	m^3	m^3	% IS	m^3	% I1	% IS
Input volume (m^3/month)	-	18379	4.7	9340	2.5	7.2
Consumed volume (m^3/month)	-	-	-	-	-	-
Leakage volume (m^3/month)	-	6207	8.5	5922	8.8	16.5
Volumetric efficiency	-		1		1	2
Energy	**kWh**	**kWh**	**%**	**kWh**	**% I1**	**% IS**
Shaft energy (Ep)	-	4297	5.0	2484	3.0	7.8
Natural energy (En)	-	5253	4.5	2669	2.4	6.8
Energy delivered to users	-	4871	6.2	3881	5.2	11.1
Minimum required energy	-	5	0.0	0	0.0	0.0
Topographic energy	-	4830	27.5	3366	26.5	46.7
Excess energy	-	0	-	0	-	-
Energy loss in friction	-	564	2.7	765	3.7	6.3
Energy dissipated in valves	-	-4561	-13.2	-3561	-9.1	-23.5
Energy loss in leakage	-	2501	11.0	2140	10.5	**20.3**
Energy loss in pumping	-	1469	5.3	819	3.1	8.2
Compensation energy	-	4081	-	656	-	-
INPUT ENERGY REDUCTION	-	**8926**	**4.4**	**4700**	**2.4**	**6.8**

The dash in the second column means that there are no differences between the initial state and itself, what makes sense. Additionally, the water volume consumed by users does not change (theoretically) even if improvements are made in the network. The reality might be different since it is observed by water companies that if the network pressure is decreased, water consumption also drops a bit. But that is another topic and herein it has been assumed that water consumption is invariable in the simulations.

As it can be seen, the network division itself already implies a saving of more than 6 thousand cubic meters per month, what improves the volumetric efficiency in 1 point and decreases the leaked volume in 8.5%. It was mentioned before that network division into DMAs is not aimed to produced energy efficiency improvements in a direct way but indirectly, thanks to active control techniques that DMA philosophy provides. However, the fact of changing the water circulation through the network pipelines by reorganising the layout already produces energy and water savings, which are not neglectable at all.

In general terms, by accounting for improvements 1 and 2, more than 12 thousand cubic meters can be saved each month. That is more than 1.3 times the average daily consumption of the city of Teruel, with more than 35 thousand inhabitants. It means reducing the leaked volume in more than 16%.

The total energy supplied by pumping has been reduced to 7.8%. That directly means a reduction of 7.8% of the variable term on the electric bill. The reduction of the shaft energy contributes to reducing pumping losses in more than 8%.

One of the most significant consequences of the measures is the reduction of the topographic energy in almost 50%, what implies less overpressure in the network and therefore, less leakage. By reducing leakage and the pressure in the network, the embedded energy loss in leakage is reduced to a 20%, a very significant value. In absolute values, this is 4,641 kWh not loss in leakage.

As a global balance, the total input energy has dropped to a 6.8%. This means 13,626 kWh less injected into the system. Environment is also a good support to boost this kind of measures and the energy reduction is translated into 58 tons of CO_2 that are avoided each year.

In order to complete the analysis, the economic assessment is needed, whether or not the energy savings will counteract the economic investment in a reasonable period of time. Since the main objective of this work is not to develop a complete project report of a specific network, only improvement number two has been account for in terms of economic aspects.

The total cost for the installation of all necessary components to conform the different DMAs affected by the PRVs specified above: 29,909.03€.

The full study is described in the project budget section of the document.

4.2. Exploring actions in the network of Sagunto

Port Sagunt and Industrial State

Improvement 1: Network division into District Metering Areas (DMA)

Similarly to Teruel, the network has been divided into DMAs as well. In this case, there exist a draft project too that has been utilised as the base support in order to transfer or translate the project to the modelling software. The model of Sagunto is better defined in Epanet, therefore the district division turns out easier to model in this case. In any case, the previous model of the network becomes a helpful guide to find the little discrepancies with the original project.

For the case of Port Sagunt, there are two main differences with respect to Teruel. First of all is that the district division project is not far at all from being executed. Although when carrying out the site inspection and reconnaissance of the facilities for this project, the works were not yet started, it might be possible that at this very moment they are carrying out the works. The second main difference is that the project has the installation of a pressure reducing valves at the entrance of all the DMAs associated, that is, downstream the break pressure tank situated after the main distribution tank of Port Sagunt. This means that this improvement also includes the installation of this PRV.

The DMA division leaves the following aspects:

- 17 DMAs are created within the network.
- Installation of a pressure reducing valve at the entrance of all sectors simultaneously. See Figure 4-5.
- Pressure set point: 25 m.w.c. during the whole day.

As it was done for Teruel, thanks to the mathematical model analysis, an annex was created with all the valves that should be close in order to reach the designed DMA distribution. Normally, these valves were already projected in the draft, however, the model was again a useful tool for the little discrepancies. Again, the annex generated, although not included in this document, is of great aid to "play" with the model even if a different layout is thought in terms of DMA distribution.

In Figure 4-5, it shown the configuration of the 17 different DMAs. Also, the location of the main pressure reducing valve is displayed. There is a pipe going backwards to feeding sectors 14, 15, 16 and 17, so the pressure reduction is also affecting these zones.

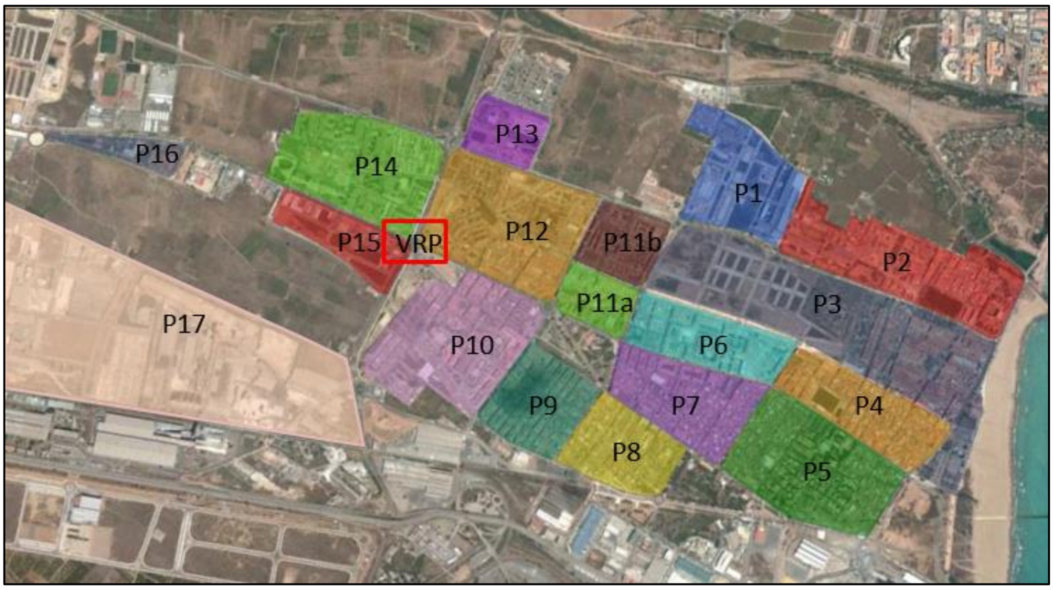


Figure 4-5. Sectors of the network of Port Sagunt and main PRV location

Improvement 2: Installation of pressure reducing valves at the entrance of some sectors

This second improvement is implemented after seen the consequences of the first action in terms of pressure. The main PRV is part of a complete restructuring of the layout of the network whereas this second implementation is already a matter of "playing" with the pressure results so that service pressure adjusts to the minimum required in order to reduce the topographic energy. This means that another configuration of the PRV is perfectly possible and the set points completely changeable. In this case, the selection and distribution of PRVs is as shown in Figure 4-6

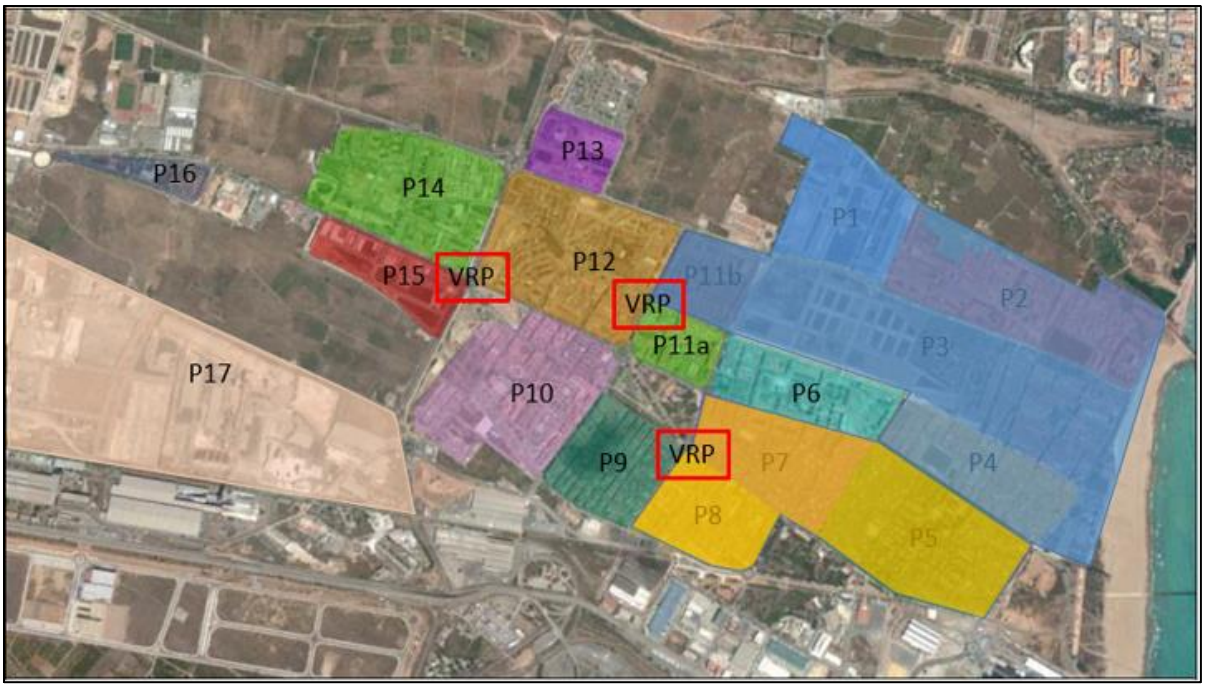


Figure 4-6. Location of the PRVs in the network of Port Sagunt

- PRV at entrance of DMAs P1, P2, P3, P4 and P11b (blue area)
  - Pressure set point: 25 m.w.c. the whole day
- PRV at entrance of DMAs P5, P7 and P8 (yellow area)
  - Pressure set point: 25 m.w.c. the whole day

4.2.1. Results of Port Sagunt + IS

As for Teruel, the new models with the improvements are passed through ITAEnergy to be compared with the initial state.

The first results that can be commented are the related with the pressure distribution in the network. In Figure 4-7, the pressure map after the improvements is observed. The metropolitan area is mainly dominated by colour green, what means that pressure values are between 25 and 35 meters of water column. There are just sectors 16 and part of sector 17 that show values between 10 and 20 m.w.c. This might be acceptable because the values are very close to 20 and there is not significant activity in these sectors more than shops or industries, and they usually have their own pressure boosters. However, this should be studied a part. One solution could be the move of the main PRV to and more advanced position. But the rest of the network perfectly comply with the 20 m.w.c. of service pressure.

In total, the average pressure before the betterments was 42.6 m.w.c and it has dropped to 32.5 m.w.c. after the main PRV and to 29.6 m.w.c. after the improvement 2. That is a 30.5% pressure reduction not neglectable at all and a very acceptable pressure for a potable water network. The reduction of topographic energy and leakage losses derived from this pressure reduction will be observed in Table 4-3 and Table 4-4.

Figure 4-7. Pressure map of the network of Port Sagunt after the improvements

Table 4-3. Results of the energy and water audits with ITAEnergy after the improvements in the network of Port Sagunt + IS

PORT SAGUNT + IS WATER SUPPLY						
Water balance	**Initial State**		**Improvement 1**		**Improvement 2**	
Input volume (m^3/month)	435862		393441		374663	
Consumed volume (m^3/month)	315169		315169		315169	
Leakage volume (m^3/month)	104472		76677		69776	
Volumetric efficiency	0.76		0.81		0.81	
Energy audit	**kWh/mth**	**%**	**kWh/mth**	**%**	**kWh/mth**	**%**
Shaft energy (Ep)	37099	38.3	33475	38.3	31916	38.4
Natural energy(En)	59694	61.7	53884	61.7	51312	61.7
Energy delivered to users	48732	50	39778	46	38307	45
Minimum required energy	33811	69	33811	85	33811	88
Topographic energy	14921	31	5967	15	4496	12
Excess energy	0	0	0	0	0	0
Energy loss in friction	6682	7	5963	7	5769	7
Energy dissipated in valves	19160	21	27031	31	28237	33
Energy loss in leakage	14895	16	8851	10	7567	9
Energy loss in pumping	5854	6	5292	6	5010	6
Compensation energy	223	0.23	67	0.08	34	0.04
INPUT ENERGY	**93247**	**100**	**86982**	**100**	**84924**	**100**

Table 4-4. Audit results of Port Sagunt + IS. Savings

SAVINGS						
Water	**Initial state**	**Improvement 1**		**Improvement 2**		
	m³	**m³**	**% IS**	**m³**	**% I1**	**% IS**
Input volume (m³/month)	-	42422	9.7	18777	4.8	14.0
Consumed volume (m³/month)	-	0	-	0	-	-
Leakage volume (m³/month)	-	27795	26.6	6901	9.0	33.2
Volumetric efficiency	-		5		1	5
Energy	**kWh**	**%** **kWh**	**% IS**	**kWh**	**% I1**	**% IS**
Shaft energy (Ep)	-	3624	9.8	1559	4.7	14.0
Natural energy (En)	-	5810	9.7	2572	4.8	14.0
Energy delivered to users	-	8954	18.4	1471	3.7	21.4
Minimum required energy	-	0	0.0	0	0.0	0.0
Topographic energy	-	8954	60.0	1471	24.7	69.9
Excess energy	-	0	-	0	-	-
Energy loss in friction	-	719	10.8	194	3.3	13.7
Energy dissipated in valves	-	-7871	-41.1	-1206	-4.5	-47.4
Energy loss in leakage	-	6044	40.6	1284	14.5	49.2
Energy loss in pumping	-	562	9.6	282	5.3	14.4
Compensation energy	-	156	-	33	-	-
INPUT ENERGY REDUCTION	-	**8564**	**9**	**2058**	**2.4**	**11.1**

Regarding the initial state, and as explained in 3.4.3, the network is receiving a 50% more energy than the required, what leaves the other 50% in losses. There is a high percentage of energy loss in valves as well as in leakage. The energy dissipated in valves is easy to understand with the distribution diagram of Port Sagunt, shown in Figure 4-8. As already explained, the break pressure tank of elevation 55 dissipates directly 20 meters of water column (minus the friction losses), and the way this simulated in Epanet is by means of a valve before the tank that dissipates all this energy. Thanks to the diagram is easy to understand the results and see why the pressure in the metropolitan area of Port Sagunt is so high, and therefore a lot of topographic energy and leakage.

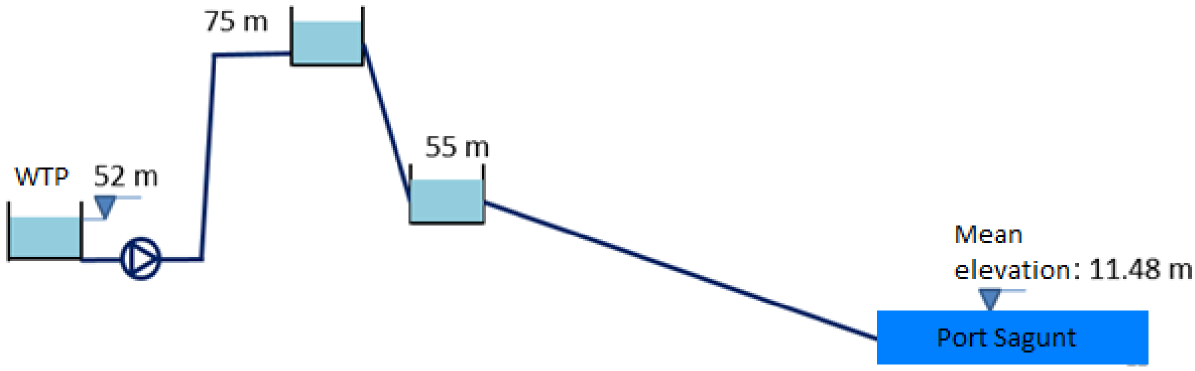


Figure 4-8. Water distribution network of Port Sagunt diagram

After the improvements, the energy loss in leakage has been reduced to almost 50% or in absolute values, 7,328 kWh per month just in embedded energy that water has. But not only energy is saved, but a reduction of 33% of the leaked volume is achieved, translated in 30 thousand cubic meters per month, that is 3 days of water consumption in Port Sagunt.

Additionally, it is quite remarkable the reduction of topographic energy to almost 70%. That is saving 10,425 kWh that will mean less overpressure in the network and less leakage.

Obviously, the negative values in the energy dissipated in valves mean that there is no saving at this point, but more energy is being dissipated through the valves since the improvements were aimed to have this effect. This prevent the network from the above mentioned topographic energy and leakage.

The general figures show that the total input energy is reduced in a 11.1% or 10,622 kWh less per month. This total energy reduction is a very acceptable value. Environmentally talking, and just considering the shaft energy reduction (not the natural energy reduction) since is the one that can be converted into electricity, it means 22 tons of CO_2 annual reduction. In this case, the value is less impressive due to the energy supply configuration of Port Sagunt, being 38.3 – 61.7% shaft and natural energy respectively.

In the case of Port Sagunt, the installation of the main pressure reducing valve for improvement 1 and the different PRVs of improvement 2 is considered in the economic assessment developed with more detail in the project budget section.

The total cost for the installation of all necessary components to conform the different DMAs affected by the PRVs specified above: 30,851.22€.

An important aftereffect derived from the analysis of the water network diagram of Port Sagunt is that it seems showy the possibility of supplying the water from the water treatment plant (WTP) by gravity as shown in Figure 4-9, the difference in elevations allows it. It is a possibility to consider in the future.

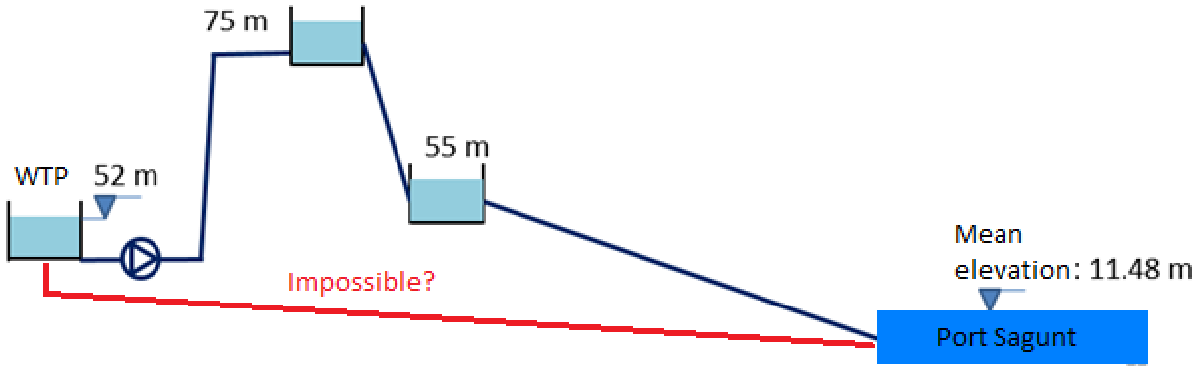


Figure 4-9. Water network of Port Sagunt diagram possibility

Sagunto City Centre and North Palancia

Improvement 1: Network division into District Metering Areas (DMA)

As it has been done with the metropolitan area of Port Sagunt, Sagunto city centre and North Palancia have been divided into district metering areas as well.

There are not too many differences between both networks regarding the action plan and schedule. In Sagunto, the network division works into DMAs are almost completed and two PRVs have already been installed. The DMA design project is the same one as for Port Sagunt. In this case, the modelling of the DMAs will help to validate the measurements with software and obviously, to account for the real improvements in terms of numbers. Since Sagunto City Centre is the only network that already had some parts of it already converted into DMAs and the PRVs already installed, this improvement is more like an update of the mathematical model rather than an actual improvement. However, as mentioned, through this update it will be possible to calculate and estimate the savings.

The district division leaves the following aspects:

- 6 DMAs are created within the network.
- Installation of PRV in Sants de la Pedra street
  - Pressure set point: 36 m.w.c. from 1 AM to 6 AM
  - Pressure set point: 55 m.w.c from 6 AM to 1 AM
- Installation of PRV in Emilio Llopis street
  - Pressure set point: 36 m.w.c. from 1 AM to 6 AM
  - Pressure set point: 55 m.w.c. from 6 AM to 1 AM

And it can be seen in Figure 4-10 how the different sectors are arranged and the location of the two pressure reducing valves.

Figure 4-10. Sectors of the network of Sagunto CC + NP and main PRVs location

The main reason for setting the pressure set points at 36 and 55 m.w.c. is because since they are already installed, users could not stand such a big pressure reduction in their service for a daily basis. It is just a matter of sensibility by the user's side. Obviously, they are taking advantage of the current high pressure and for the moment, the city hall is not willing to receive too many complaints if they reduce the pressure.

Improvement 2: Installation of a PRV at the entrance of the DMA of North Palancia (S4)

Due to the easiness of controlling the sector of NP and therefore the installation of a pressure reducing valve, it has been modelled this valve with a pressure set point of 25 m.w.c. the whole day.

In Figure 4-10, sector 4 corresponding to North Palancia has only three entry points and the one in the middle and that of the right are closed. So the only way for water to enter the sector is the pipe on the left, where the PRV is to be installed.

Improvement 3: Change of the pressure set points of the main PRVs

It is reasonable to lower the pressure set points since they are still high. As it will be shown in the results, the installation of the PRV at the entrance of NP does not have the desirable energy reduction. It is worthy to mention how this measure is an operational measure. There is no need for an economic investment but just changing the working point of a network element.

- Pressure set point: 36 m.w.c the whole day for both PRVs.

It must be taken into account that the set point of the valve must always comply with the service pressure stablished for the network, as a mandatory requirement.

4.2.2. Results of Sagunto CC + NP

The results description is similar to that of Port Sagunt. The main interest lays under the effects of the PRVs at the entrance of the main sectors.

First of all, it should be noted that the mean pressure of the network was 58.6 m.w.c. It is already a high value and that is why the topographic energy is high, as well as the leakage. With the installation of the pressure reducing valves and their initial set points, the mean pressure of the network decreases to 55.1 meters of water column. It is not the desirable result but it makes sense if the mean pressure is 58 m.w.c and the valves regulate it to 56 most part of the day.

By changing the set points of the valves, mean pressure of the network drops to 48 m.w.c. It is still high but a ten meters reduction is already noticeable. However, it must be marked that Sagunto is no longer as flat as Port Sagunt and there are some elevated points. In order to supply the highest nodes of the system with the required pressure, it cannot be reduced as much as desired. One cannot forget that the modelling is based on a real water supply network and there are real users and real problems out there.

Figure 4-11 shows the pressure map of the network of Sagunto after the improvements. The simulation time is the less favourable one, when demand is higher and pressure is the lowest, so that the least favourable points of the network are supplied with the service pressure.

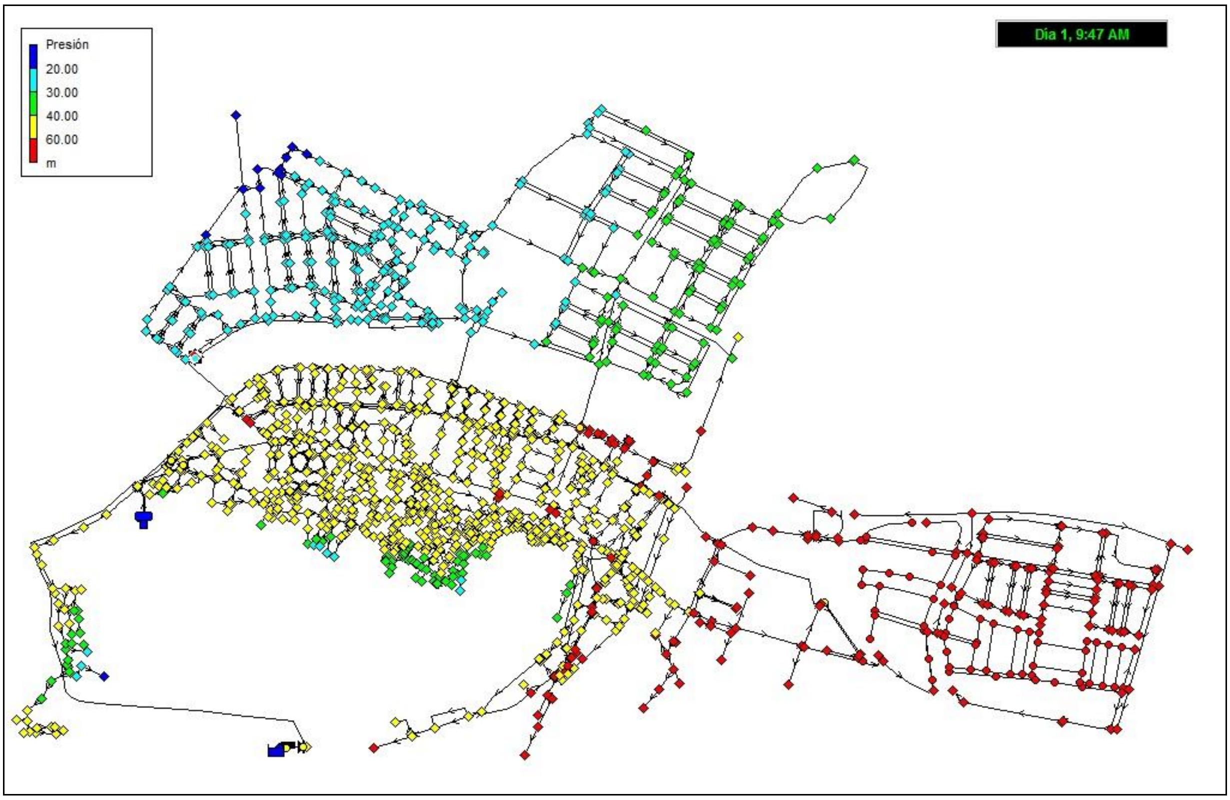


Figure 4-11. Pressure map of the network of Sagunto CC + NP after the improvements

A couple of things are worth mentioned. The first one is that high pressures are still observable throughout the network. There are not any valves for sectors 2.2 or 3.1 and sector 3.2 is the most elevated one, so pressure cannot be reduced. However, for sectors 1 and 2.1 there is still some margin for the pressure to be lowered. The second aspect is that the positive side is the fact that this is a real case scenario from which measures can be observed on site and on simulations. The fact of tuning the set points of the valves and being able to observe the results gives the control agents a very good tool.

Regarding the energy results, they can be observed in Table 4-5 and Table 4-6.

Table 4-5. Results of the energy and water audits with ITAEnergy after the improvements in the network of Sagunto CC + NP

SAGUNTO CC + NP								
Water balance	**Initial State**		**Improvement 1**		**Improvement 2**		**Improvement 3**	
Input volume (m^3/month)	136668		133676		131144		126442	
Consumed volume (m^3/month)	94369		94369		94369		94369	
Leakage volume (m^3/month)	43647		39732		38925		32351	
Volumetric efficiency	0.68		0.70		0.70		0.74	
Energy audit	**kWh/mth**	**%**	**kWh/mth**	**%**	**kWh/mth**	**%**	**kWh/mth**	**%**
Shaft energy (Ep)	30008	78.6	29345	78.6	28788	78.6	27771	78.6
Natural energy (En)	8158	21.4	7979	21.4	7828	21.4	7547	21.4
Energy delivered to users	20103	52	19239	52	17635	48	16390	46
Minimum required energy	9793	49	9793	51	9793	56	9793	60
Topographic energy	10312	51	9444	49	7845	44	6595	40
Excess energy	0	0	0	0	0	0	0	0
Energy loss in friction	3903	10	3811	10	3754	10	3465	10
Energy dissipated in valves	0	0	1358	4	3010	8	5018	14
Energy loss in leakage	9270	24	7945	21	7713	21	5709	16
Energy loss in pumping	5177	13	5060	14	4964	13	4793	14
Compensation energy	16	0.04	-70	-0.19	26	0.07	-63	-0.18
INPUT ENERGY	**38468**	**100**	**37343**	**100**	**37102**	**100**	**35313**	**100**

Table 4-6. Audit results of Sagunto CC + NP. Savings

SAVINGS										
Water	Initial State		Improvement 1		Improvement 2			Improvement 3		
	m³		m³	% IS	m³	% I1	% IS	m³	% I1	%IS
Input volume (m³/month)	-		2992	2.2	2532	1.9	4.0	4702	5.4	7.5
Consumed volume (m³/month)	-		0	-	0	-	-	0	-	-
Leakage volume (m³/month)	-		3915	9.0	807	2.0	10.8	6574	18.6	25.9
Volumetric efficiency	-			2		0	2		4	6
Energy	**kWh**	**%**	**kWh**	**% IS**	**kWh**	**% I1**	**% IS**	**kWh**	**% I1**	**% IS**
Shaft energy (Ep)	-		664	2.2	557	1.9	4.1	1017	5.4	7.5
Natural energy (En)	-		179	2.2	151	1.9	4.0	281	5.4	7.5
Energy delivered to users	-		864	4.3	1605	8.3	12.3	1245	14.8	18.5
Minimum required energy	-		0	0.0	0	0.0	0.0	0	0.0	0.0
Topographic energy	-		868	8.4	1599	16.9	23.9	1250	30.2	36.0
Excess energy	-		0	-	0	-	-	0	-	-
Energy loss in friction	-		92	2.4	57	1.5	3.8	0	9.1	11.2
Energy dissipated in valves	-		-1358	100.0	-1653	-121.7	100.0	-2008	-269.6	100.0
Energy loss in leakage	-		1324	14.3	233	2.9	16.8	2003	28.1	38.4
Energy loss in pumping	-		117	2.3	96	1.9	4.1	170	5.3	7.4
Compensation energy	-		86	-	-96	-	-	89	-	-
INPUT ENERGY REDUCTION	-		**1125**	**3**	**242**	**0.6**	**3.6**	**3156**	**5.4**	**8.2**

As it has already been commented, with respect to the initial situation, almost an extra 50% more than the required energy is been supplied to the system. The other 52% is being delivered to users. There is also an important amount of topographic energy (26.8% out of the total energy of the system). It can be explained from Figure 4-12. Water is being pumped from the WTP at 52 meters to the main tank at 110 meter high. The weighted mean elevation of Sagunto is 48 meters high what means that an overpressure will govern the network (except for the highest points of the system). There are 62 available meters of water column that with the head losses they are translated into the 58.6 m.w.c of mean pressure previously commented.

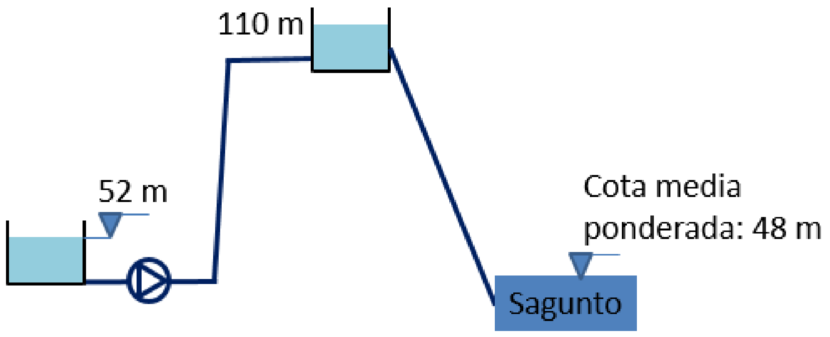


Figure 4-12. Distribution diagram of SCC + NP

If now, the first improvement is taken and the pressure reducing valve is set at the entrance of Sagunto, where there are almost 60 available meters, and set it to 55 meters of set point, the progress is scarce.

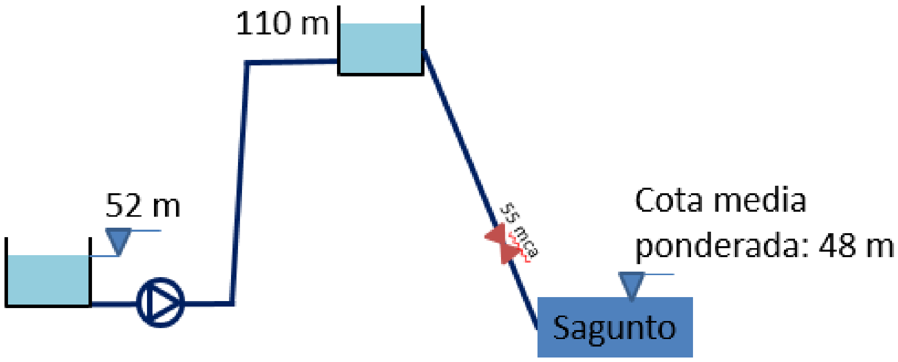


Figure 4-13. Distribution diagram of SCC with PRV

However, the leaked volume is reduced to a 9% what is equivalent to saving almost 4 thousand cubic meters per month, and the total input energy is lowered a 3 per cent.

If improvement 3 is considered as a feasible option, things start to change a bit more with optimal figures. The leaked volume falls up to a 26% or more than 6 thousand cubic meters per month. That is already an important reduction just in terms of water. And it is important to remember that this saving is not at the expense of water incomes for the water company since leaked volumes are not billed.

The topographic energy also receives and important cutting of 36% or 3,718 kWh per month. This energy is no longer supplied to the users in the form of overpressure and this reduction explains the savings in the leakage losses, which is reduced up to a 38% or 3,560 kWh.

The total energy reduction of the system is of 8.2%, what means that 3,156 kWh are saved every month of the complete supply. Since Sagunto relies much more in pumping than in natural energy, the shaft energy reduction is in total 2,238 kWh of electric energy. The CO_2 reduction is 9.6 tons less every year.

The positive side in the economic assessment for Sagunto's improvements is that improvement 3 is an operational measure, and therefore it implies no economic investment taking into account that improvement 1 is already implemented.

5. CONCLUSIONS

This project goes through the description, assessment and critical analysis of a methodology that helps to study pressurized urban water networks, understand them and realize an accurate audit of energy efficiency terms involving hydraulic characteristics of water networks.

As a main summary of how to proceed, first, a diagnostic will give an overall picture of the system status. It will tell how energies are distributed and, in a more informative way, the ideal efficiency of the network, how far I can go to improve the energetic status of the system by knowing the boundaries of this improvement. If a system is liable to be improved is because the difference between the ideal efficiency and the real or current efficiency of the network are far from being close.

But in order to better understand the energy distribution of a water network, additional audits are needed by means of, first a water audit and after an energy audit. The former will tell how water is being managed by the system, if there are water leaks and how important they are, whereas the latter will go deeper in the understanding of energy losses. The need for distinguishing the different energies in the system is key to be able to improve it. It has been seen how the software is able to break down the different energy losses and account for them so that the main need can be addressed. If there are friction losses, the piping system should be inspected, if there are leakage energy losses also the pipeline should be checked but also high overall pressures may be the cause. If there is topographic energy, then the layout of the network induces this energy in the system automatically, but there are means to reduce it by the installation of pressure reducing valves as it has been described, or ways to recover it by means of PATs. If there are pumping losses, then the pumping equipment is to be checked or replaced, etc.

In general, there is a broad overview on how to prepare a case study to be analysed, understood and improved by means of the tools described in the work. And these tools are the second main part of the study. Although they are not perfect, they ease and prepare the path to follow in the future, the future understood as the improvements to be done to ameliorate the energy efficiency of a pressurized water network. From EAGLE for the diagnose, ITAFugas for leakage allocation, Epanet for hydraulic modelling and ITAEnergy for energy audit. Each of them conforms an important aspect of the procedure and provides its added value to the chain.

As a key aspect of the above-mentioned, it is advisable to point out the necessity of a reliable mathematical model for pursuing good results. The energy audit is completely based on the mathematical model from Epanet and an incomplete or untrustworthy model will lead to the same results. The more information about the network is available the more calibrated the model will be and vice versa. Otherwise, a much bigger effort is needed in the calibration/mathematical model update phase. This work has been based on the already existing mathematical models of two networks.

And as it has been shown all along the document, every different step, aspect or point has been proven through these two different case studies, Teruel and Sagunto. The fact of having two alternatives in the form of case study is not a coincidence but the completion of a work that proves the validity of the methodology in various conditions and scenarios and, as mentioned before, the existence of a starting point being the mathematical models. The differentiated characteristics of each of the networks, being Sagunto also divided into two subnetworks as well, allows to validate the results provided by the software. On the one hand, the way this document has been approached leaves less margin of analysis for each of the networks, with various different strategies of improvement that have not been tackled due to a lack of resources than if only one case study would have been considered. On the other hand, the more versatile approach undertaken here induces to results of different nature and evidences the success of an implicit sensibility analysis of the methodology.

The analyses made during the project have also proven some different possibilities of improvement that are liable to be studied in the future. In the case of Teruel, the model has demonstrated itself to be a robust way to verify the network division into DMAs. Although DMA strategy is not aimed to improve the energy efficiency of a system directly but indirectly, it has been verified that DMA division can indeed lead to energy consumption reduction. And the DMA division considered in this project for Teruel is not optimal, with some sectors or areas being difficult to isolate in DMA as clarified in section 4.1. Therefore, the analysis performed leaves margin of improvement for both a better distribution of the DMAs and also the placing of the PRVs, since there are still areas with enough pressure to be reduced. In the case of Sagunto, there is a clear candidate for future analyses through ITAenergy, the implementation of a water supply by gravity in Port Sagunt. The energy excess dissipated in the valves and the overpressures governing the network before the installation of the main PRV confirm that the idea is not out of the scope of future candidate measures.

The main conclusion of the previous paragraph is the fact of how thanks to the analysis step by step followed in the document, new improvements, developments or techniques come along that liable to be applied to the system under study. And the possession of the mathematical model and the energy audit software makes energy assessments straight forward. And it is this easiness what provides the added value to this project.

6. FUTURE WORK

The energy efficiency field is far from being over. All the way around, now more than ever, a good management of the current facilities, infrastructures, companies and resources in general is sought in all the different aspects that can be managed. Water management is not out of this scope and still, energy efficient water networks are far from being a reality at least, in a big scale.

Works like this project are support material in the goal of water network efficiency management and help to better understand what energy efficiency in water networks means and how to improve it. There are two lines of future work to be developed related to this document. The first one that aims to improve this specific study, problems found in the methodology, limitations of the tools used, discrepancies, etc. and a second current targeting the management of efficient water networks in general terms. This project can be an option as well as other methodologies and/or strategies might be equally legitimate.

Beginning with improvement of the methodology itself described in this document, some remarks can be made. And they can be structured as well the way this work is.

The diagnostic phase is a preliminary approach to the network. By making use of the EAGLE tool, the user is limited to the boundaries of this tool. The main problem resides in the definition of the network topology when we are dealing with complex layouts with end or intermediate tanks, booster pumps in the middle of the network or even combinations of both. The diagnostic has to be performed in a simplified basis. Therefore, the simpler the network is, the better the results obtained. With complex networks, the results must be understood as a first definition on how the main energies are distributed within the network but not as a statement of results. Additionally, the pre-audit frame that is found in EAGLE cannot be trusted completely as the network is more complex. Though it can be sufficient for irrigation networks for example.

A water audit is never an easy and direct task. It is not that there are wrong aspects about it herein described, the only problem is that a water audit must be carried out properly. And this consumes slightly more resources than the devoted to gather trustful information. Determining the apparent losses or the real loss volume is not simple. However, ITAFugas has indeed a limitation in the way it exports the results to Epanet. The amount of water that it estimates as real losses are assigned to Epanet in the form of emitters to the consumption nodes. Nevertheless, the apparent losses are added to the base demand of these consumption nodes. This prevents the model from retrieving the initial information for the base demands since they are no longer available. They are upgraded with the apparent losses. Epanet has the option to introduce different demands to the same node. Therefore, to solve this issue, it may be interesting to leave the initial base demand of the node intact and add the whole demand (base demand + apparent losses) in the form of a second demand.

The energy audit is realized with ITAEnergy. This software has been the main support together with Epanet to obtain the main results of this study. However, some improvements could be introduced in the future to this software.

One of the main causes for inefficiencies is the pumping. The problem is that not only the pump efficiency counts, but the whole pumping station should be considered. ITAEnergy only contemplates the efficiency curve that has been introduced in Epanet and this should be corrected. It would be a good advance to have the possibility in ITAEnergy to calculate the efficiency of the whole group or pump station.

And finally, on of the key aspects of this work, the mathematical model. Having a trustworthy model of the water network under study is basic and very important. Keeping up-to-date the mathematical model implies a continuous dedication, in charge of the water company. An up-to-date model allows the user to prove and keep track of the energy footprints that any measure undertaken upon the network may have: the addition of an important water consumer, the reparation of a pipeline, the improvement of the pumping equipment, the replacement of a pipe by a bigger diameter, a change in the operation conditions of the network (different pumping hours, closing of valve…) and a long etcetera. The easiness of use of ITAEnergy makes fast and cost-effective the analysis assessment of a well-defined and trustful mathematical model.

In the line of future development regarding energy efficiency in water systems, there is a lot still left. Companies should join efforts in the benefit of everybody (even the companies themselves). It is quite striking to realise the different strategies that water companies can follow to pursue the same objectives. Even in the same country and region too, different perspectives regarding water networks management are found. All of them valid, yes, but still have proven inefficient.

The installation of more efficient pumps. It is nowadays more frequent to find pumps reaching 90% of efficiency with current technology. The installation of PATs. There is each time more and more information about this technology, the smart metering, water leak control management, etc.

However, one of the most important paths to follow has to do with people. People is the most powerful tool to fix things. Economy, environment and society, but the first two are ruled by the third. It has been proven throughout the whole document the important effect that pressure has on energy costs regarding water networks. Yet, social awareness is several times not achieved. The population complains when the tap pressure is reduced from one day to another. It is normal though, but it is to the local governments to make people aware of the situation and teach them. Water supplies with 7 bar (like in the case of Teruel for example) of pressure is unconceivable and yet, it is happening.

The changing in direction is happening thanks to European directives or set goals for a specific year, but the road is still long and rough. The only way to achieve the goals it by working together water companies, local authorities, European ruler and of course, society.

7. BIBLIOGRAPHY

Alkasseh, J. M., Adlan, M., Abustan, I., Aziz, H., & Mohamad, A. (2013). Applying Minimum Night Flow to Estimate Water Loss. Water Resour Manage, 1439–1455. https://doi.org/10.1007/s11269-012-0247-2

Almandoz, J., Cabrera, E., Arregui, F., Cabrera Jr., E., & Cobacho, R. (2005). Leakage Assessment through Water Distribution Network Simulation. Journal of Water Resources Planning and Management, 131(6), 458–466. https://doi.org/10.1061/(ASCE)0733-9496(2005)131:6(458)

American Water Works Association. (2012). Water Loss Control: IWA / AWWA Water Audit Method.

Andrés, L. (2014). Elaboración del modelo matemático de la red de abastecimiento de agua potable de la ciudad de Teruel. Propuesta de sectorización y mejora. Universitat Politècnica de València.

Asociación Española de Abastecimiento de Agua y Saneamiento. (2016). Suministro de agua potable y saneamiento en España.

Bolognesi, A., Bragalli, C., Lenzi, C., & Artina, S. (2014). Energy efficiency optimization in water distribution systems. Procedia Engineering, 70, 181–190. https://doi.org/10.1016/j.proeng.2014.02.021

Cabrera, E. (2005). Una aproximación a la problemática de las pérdidas de aguas en redes urbanas.

Cabrera, E. (2011). El binomia agua-energía ¿un asunto de moda o de interés real? Fundación Ciudadanía y Valores. Retrieved from http://www.funciva.org/uploads/ficheros_documentos/1321878093_agua_y_energĺa_asunto_de_moda_o_de_interes_real.pdf

Cabrera, E., Almandoz, J., Arregui, F., & García-Serra, J. (1999). Auditoría de redes de distribución de agua. Ingeniería Del Agua, 6(diciembre), 387–399.

Cabrera, E., Gómez, E., Cabrera Jr., E., Soriano, J., & Espert, V. (2015). Energy Assessment of Pressurized Water Systems. Journal of Water Resources Planning and Management, 141(8), 1–12. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000494.

Cabrera, E., Pardo, M. Á., Cobacho, R., & Cabrera Jr., E. (2010). Energy Audit of Water Networks. Journal of Water Resources Planning and Management, 136(December), 669–677. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000077

Calvo, I. P., Carlos, J., Estrada, G., Cañas, R., & Luque, R. L. (2006). Depósitos de regulación en cabecera de redes hidráulicas a presión. Revista Iberoamericana de Ingeniería Mecánica, 10, 81–96.

Corominas, J. (2010). Agua y Energía en el riego, en la época de sostenibilidad. Ingeniería Del Agua, 17(3), 15. https://doi.org/10.4995/ia.2010.2977

Del Teso March, R. (2016, November 25). Simulación de la recuperación de energía mediante bombas trabajando como turbinas a partir del análisis energético de la red de abastecimiento de agua potable del municipio de Picanya. Universitat Politècnica de València. Retrieved from https://riunet.upv.es/handle/10251/74620

El País, E. (2015). Tribulaciones hídricas urbanas. Ediciones El País.

EPA, United States Environmental Protection Agency (2013). Water Audits ans Water Loss Control, (EPA 816-F-13-002), 1–7.

Eurostat. (2016). Energy, transport and environment indicators. Luxembourg. https://doi.org/10.2785/138586

Gómez, E. (2016). Caracterización y mejora de la eficiencia energética del transporte de agua a presión. Universitat Politècnica de València.

Gómez, E., Cabrera, E., Soriano, J., & Balaguer, M. (2016). On the weaknesses and limitations of EPANET as regards energy. Water Science and Technology: Water Supply, 16(2), 369–377. https://doi.org/10.2166/ws.2015.145

INE, Instituto Nacional de Estadística. (2016). Encuesta sobre el Suministro y Saneamiento del Agua, año 2014.

INE, Instituto Nacional de Estadística. (2017). *Tabla2911*. [online] Available at: http://www.ine.es/jaxiT3/Datos.htm?t=2911 [Accessed 24 Jan. 2017].

INE, Instituto Nacional de Estadística. (2017). Tabla2903. [online] Available at: http://www.ine.es/jaxiT3/Datos.htm?t=2903 [Accessed 25 Jan. 2017].

IRENA, International Renewable Energy Agency. (2012). Hydropower. Renewable Energy Technologies: Cost Analysis Series, 1. Power Sector (3/5), 44. Retrieved from http://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-hydropower.pdf

Lazarova, V., Choo, K.-H., & Cornel, P. (2012). Meeting the challenges of the water - energy nexus: the role of reuse and wastewater treatment.

López Martín, F., Cabrera Millet, M., Cuadrat, J., Saz Sánchez, M. and Vicente Serrano, S. (2007). Atlas climático de Aragón. 1st ed. [Zaragoza]: Servicio de Información y Educación Ambiental, Dirección General de Calidad Ambiental y Cambio Climático.

Lozano, J. I. (2015, June 5). Análisis del abastecimiento de agua potable de sagunto. Modelo matemático y propuesta de mejoras. Universitat Politècnica de València. Retrieved from https://riunet.upv.es/handle/10251/51318

MINETUR, Ministerio de Energía, Turismo y Agenda Digital. (2014). Factores de emisión de CO2 y coeficientes de paso a energía primaria de diferentes fuentes de energía final consumidas en el sector de edificios en España, 16.

United Nations. (2016). World Cities Report. World Cities Report.

Red Eléctrica de España. (2016). Preliminary Report 2016.

Spang, E. S., Moomaw, W. R., Gallagher, K. S., Kirshen, P. H., & Marks, D. H. (2014). The water consumption of energy production: an international comparison. Environmental Research Letters, 9(10), 105002. https://doi.org/10.1088/1748-9326/9/10/105002

De Teruel, Aguas (2015). Proyecto de sectorización de la red de agua potable de Teruel.

The Convention. (2016). Paris Agreement, 1–16.

United Nations World Water Assessment Programme. (2014). Water and Energy - Executive summary. WWAP. (Vol. 1).

PROJECT BUDGET

INDEX

1. NEED FOR A BUDGET

Although the main idea for this project is to describe and analyse a methodology aimed to assess the energy use in a pressurized urban water network, the outcomes of this work are clear and simple, try to optimize and make more energy efficient the water network under study. In order to do so, improvements in the network are needed, as detailly described in the report. These improvements may imply an economic investment or may not if the measures are operational. But some of the measures described do need this investment.

The budget described below has been realized with a specific software called PRESTO. Although the program offers a much deeper level of detail for each of the element's description, only three levels have been considered: chapter, first level (0X), activity, second level (0X.0X) and work item, third level (0X.0X.0X). Next levels would include the amount of man power needed for each of the elements, the machinery, raw materials, etc. which are out of the description detail of this budget.

The budgets include a final summary at the end of it. In this summary, two aspects must be mentioned:

1. Taxes

   Taxes have been added in the form of IVA (21%). However, given the nature of the works, this tax may not apply. The kind of works that are to be done in these projects are handled by two different parties generally. The first one is the water company that is in charge of managing the water infrastructure and the water billing. If the company is going to bear the expenses of works, it makes no sense to apply the IVA to itself. And the second interested party is usually the town council which asks for the works to improve the public infrastructures. Since taxes are eventually payed to the local government, they will not ask to add the IVA into the final budget.

2. Direct + Job Overhead

   This is added to the final budget as a 10% of the total amount. This value represents two parts. The first one is the profit that the company is expecting to get over the budget price. And the job overhead contemplates any possible setbacks that may lead into cost overruns. This 10% is considered a low estimate, but considering the points described above and the fact that this budget is considered more from a theoretical perspective, the 10% will be left.

2. TERUEL

The definition of the budget for Teruel's case study takes into account improvement 2 described in section 4.1. The main work includes the installation of several pressure reducing valves at the entrance of different districts metering areas (DMAs). Before the installation of these valves it is obvious that the division of the network into these DMAs is needed, but since this is not a civil work project, only the budget for one of the improvements has been considered.

For the installation of the valves, there are three distinguishable phases that will apply to each of the valves in each of the different districts considered:

1. Earthworks: This accounts for the trial pit opening for the construction of the water chamber where the valve will be placed
2. Mechanical and civil works: This activity considers the construction of the water chamber itself and the installation of the different elements and pieces that conform a typical pressure reducing valve installation. It must be noted that the price of the elements already includes the necessary civil works as well as the installation and transport of the element. The technical explanation for the choice of the different elements depicted in the budget is not described.
3. Finish: The replenishment of the pavement after ground works are done is needed and an overall estimated price for these kind of works is depicted in this activity.

The diameter election is a function of the existing pipeline in the network however, the exact location of the water chamber has not been studied and therefore, the situation of the ground conditions, accessibility, etc. cannot be accounted for, with the discrepancies this may cause in a real budget scenario. Nevertheless, exact real conditions can never be reflected and that is why job overheads are contemplated in budgets.

With all the previously described, this layout has been followed for all the different DMAs pressure reducing valves installation.

The total cost of the improvement is reflected in the budget summary, at the end of the budget break down.

This cost represents a total amount of 29,909.03€ before profit and jobs overhead and 32,899.93€ before taxes, price that will be considered for analysis.

To make a cost-benefit analysis, Table 4-2 is used. From the table, the energy savings expected from improvement 2 are 4,700 kWh/month. With an approximate unit price of energy of 0.1€/kWh, there is an annual saving of 5,640€. This results in a return of investment (ROI) of:

$$ROI = \frac{Initial\ investment\ (€)}{Anual\ savings\ (€/year)} = \frac{32{,}899.93}{5{,}640} = 5.8\ years$$

There are a few remarks to do about this calculation. First of all, the energy term for the annual savings considered. The total amount of energy reduction has been chosen, when only shaft energy savings result in electric energy savings. This is true however, a lot of different energy savings are not considered in the assumption and do have a final impact that cannot be accounted for in this budget description; reduction of maintenance costs associated to a pressure reduction operated network, reduction of reparations associated to leaks produced by a higher network service pressure, and most description; reduction of maintenance costs associated to a pressure reduction operated network, reduction of reparations associated to leaks produced by a higher network service pressure, and most important, energy savings due to water reduction volume injected into the network. There are 5,922 m^3 of water savings per month or 71,064 m^3 per year. Common prices for water production per cubic meter in Spain are rated between 0.25€ and 1€[1], with an average value of 0.625€/m^3, resulting in 44,415€ due to water savings. But since this assessment is focused on the energy efficiency of the system, only the value previously indicated is used. Nevertheless, it cannot be neglected

So, as a rough analysis of cost-benefit study, the previous datum will be used.

Either way, the total investment calculated for the works described fall within complete acceptable and affordable values for this kind of works, and the recovery period is also very acceptable.

[1] Water production rates vary depending on the main water source from where water is extracted. This price ranges have been obtained by crossing information provided by some of the water management companies.

ESTIMATE AND TAKE-OFF LINES

CODE	DESCRIPTION	UNITS	LENGTH	WIDTH	HEIGHT	QUANTITY	PRICE	AMOUNT
01	**DMA 6**							
01.01	**Earthworks**							
01.01.01	**M2 PAVEMENT DEMOLITION 15 CM**							
Act0010			2.80	2.30		6.44		
						6.44	10.74	69.17
01.01.02	**m³ TRIAL PIT LOOSE SOIL STREET CHAMBER**							
Act0010		1	2.50	2.00	1.80	9.00		
						9.00	3.55	31.95
	TOTAL 01.01							**101.12**
01.02	**Mechanical and Civil Works**							
01.02.01	**GATE VALVE DN=200 mm**							
Act0010		2				2.00		
						2.00	810.84	1,621.68
01.02.02	**ud GATE VALVE DN=80 mm**							
Act0010		2				2.00		
						2.00	472.85	945.70
01.02.03	**ud PRESSURE REDUCING VALVE**							
Act0010		1				1.00		
						1.00	4,253.81	4,253.81
01.02.04	**UD BEND 90º HºFº ø 80 F.F.**							
Act0010		2				2.00		
						2.00	45.73	91.46
01.02.05	**UD TEE Hº Fº ø 200/80 F.F.F.**							
Act0010		2				2.00		
						2.00	62.95	125.90
01.02.06	**UD REDUCT. Hº Fº ø 300/200 F.F.**							
Act0010		2				2.00		
						2.00	200.00	400.00
01.02.07	**UD PIPE DISMANTLING JOINT HºFº ø200x200 F.F.**							
						1.00	45.35	45.35
01.02.08	**UD AIR VENT T.F. ø 80 PN-10**							
						1.00	527.61	527.61
	TOTAL 01.02							**8,011.51**
01.03	**Finish**							
01.03.01	**m² PAVEMENT M.B.C. TYPE D-12 6 CM.**							
Act0010			2.80	2.30		6.44		
						6.44	25.84	166.41
	TOTAL 01.03							**166.41**
	TOTAL 01							**8,365.87**

ESTIMATE AND TAKE-OFF LINES

CODE	DESCRIPTION	UNITS	LENGTH	WIDTH	HEIGHT	QUANTITY	PRICE	AMOUNT
02	**DMA 7**							
02.01	**Earthworks**							
02.01.01	**M2 PAVEMENT DEMOLITION 15 CM**							
Act0010			2.80	2.30		6.44		
						6.44	10.74	69.17
02.01.02	**m³ TRIAL PIT LOOSE SOIL STREET CHAMBER**							
Act0010		1	2.50	2.00	1.80	9.00		
						9.00	3.55	31.95
	TOTAL 02.01							**101.12**
02.02	**Mechanical and Civil Works**							
02.02.02	**ud GATE VALVE DN=80 mm**							
Act0010		2				2.00		
						2.00	472.85	945.70
02.02.03	**ud PRESSURE REDUCING VALVE**							
Act0010		1				1.00		
						1.00	2,325.04	2,325.04
02.02.04	**UD BEND 90º HºFº ø 80 F.F.**							
Act0010		2				2.00		
						2.00	45.73	91.46
02.02.08	**UD AIR VENT T.F. ø 80 PN-10**							
						1.00	527.61	527.61
02.02.01	**GATE VALVE DN=100 mm**							
Act0010		2				2.00		
						2.00	484.83	969.66
02.02.05	**UD TEE Hº Fº ø 100/80 F.F.F.**							
Act0010		2				2.00		
						2.00	62.95	125.90
02.02.07	**UD PIPE DISMANTLING JOINT HºFº ø80x200 F.F.**							
						1.00	45.35	45.35
	TOTAL 02.02							**5,030.72**
02.03	**Finish**							
02.03.01	**m² PAVEMENT M.B.C. TYPE D-12 6 CM.**							
Act0010			2.80	2.30		6.44		
						6.44	25.84	166.41
	TOTAL 02.03							**166.41**
	TOTAL 02							**5,298.25**

ESTIMATE AND TAKE-OFF LINES

CODE	DESCRIPTION	UNITS	LENGTH	WIDTH	HEIGHT	QUANTITY	PRICE	AMOUNT
03	**DMA 11**							
03.01	**Earthworks**							
03.01.01	**M2 PAVEMENT DEMOLITION 15 CM**							
Act0010			2.80	2.30		6.44		
						6.44	10.74	69.17
03.01.02	**m³ TRIAL PIT LOOSE SOIL STREET CHAMBER**							
Act0010		1	2.50	2.00	1.80	9.00		
						9.00	3.55	31.95
	TOTAL 03.01							**101.12**
03.02	**Mechanical and Civil Works**							
03.02.01	**GATE VALVE DN=200 mm**							
Act0010		2				2.00		
						2.00	810.84	1,621.68
03.02.02	**ud GATE VALVE DN=80 mm**							
Act0010		2				2.00		
						2.00	472.85	945.70
03.02.03	**ud PRESSURE REDUCING VALVE**							
Act0010		1				1.00		
						1.00	4,253.81	4,253.81
03.02.04	**UD BEND 90º HºFº ø 80 F.F.**							
Act0010		2				2.00		
						2.00	45.73	91.46
03.02.05	**UD TEE Hº Fº ø 200/80 F.F.F.**							
Act0010		2				2.00		
						2.00	62.95	125.90
03.02.07	**UD PIPE DISMANTLING JOINT HºFº ø200x200 F.F.**							
						1.00	45.35	45.35
03.02.08	**UD AIR VENT T.F. ø 80 PN-10**							
						1.00	527.61	527.61
	TOTAL 03.02							**7,611.51**
03.03	**Finish**							
03.03.01	**m² PAVEMENT M.B.C. TYPE D-12 6 CM.**							
Act0010			2.80	2.30		6.44		
						6.44	25.84	166.41
	TOTAL 03.03							**166.41**
	TOTAL 03							**7,879.04**

ESTIMATE AND TAKE-OFF LINES

CODE	DESCRIPTION	UNITS	LENGTH	WIDTH	HEIGHT	QUANTITY	PRICE	AMOUNT
04	**DMA 13&14**							
01.01	**Earthworks**							
01.01.01	**M2 PAVEMENT DEMOLITION 15 CM**							
Act0010			2.80	2.30		6.44		
						6.44	10.74	69.17
01.01.02	**m³ TRIAL PIT LOOSE SOIL STREET CHAMBER**							
Act0010		1	2.50	2.00	1.80	9.00		
						9.00	3.55	31.95
	TOTAL 01.01							**101.12**
01.02	**Mechanical and Civil Works**							
01.02.01	**GATE VALVE DN=200 mm**							
Act0010		2				2.00		
						2.00	810.84	1,621.68
01.02.02	**ud GATE VALVE DN=80 mm**							
Act0010		2				2.00		
						2.00	472.85	945.70
01.02.03	**ud PRESSURE REDUCING VALVE**							
Act0010		1				1.00		
						1.00	4,253.81	4,253.81
01.02.04	**UD BEND 90º HºFº ø 80 F.F.**							
Act0010		2				2.00		
						2.00	45.73	91.46
01.02.05	**UD TEE Hº Fº ø 200/80 F.F.F.**							
Act0010		2				2.00		
						2.00	62.95	125.90
01.02.06	**UD REDUCT. Hº Fº ø 300/200 F.F.**							
Act0010		2				2.00		
						2.00	200.00	400.00
01.02.07	**UD PIPE DISMANTLING JOINT HºFº ø200x200 F.F.**							
						1.00	45.35	45.35
01.02.08	**UD AIR VENT T.F. ø 80 PN-10**							
						1.00	527.61	527.61
	TOTAL 01.02							**8,011.51**
01.03	**Finish**							
01.03.01	**m² PAVEMENT M.B.C. TYPE D-12 6 CM.**							
Act0010			2.80	2.30		6.44		
						6.44	25.84	166.41
	TOTAL 01.03							**166.41**
	TOTAL 04							**8,365.87**
	TOTAL							**29,909.03**

ESTIMATE SUMMARY

CODE	DESCRIPTION	UNITS	LENGTH	WIDTH	HEIGHT	QUANTITY	PRICE	AMOUNT
01	DMA 6						8,365.87	27.84
02	DMA 7						5,298.25	17.82
03	DMA 11						7,879.04	26.50
04	DMA 13&14						8,365.87	27.84

DIRECT + JOBSITE OVERHEAD	**29,909.03**
10.00........ % Home overhead and profit	2,990.90
ESTIMATE BEFORE IVA	**32,899.93**
21% IVA	6,908.99
ESTIMATE	**39,808.92**

This estimate is THIRTY-NINE THOUSAND EIGHT HUNDRED AND EIGHT EUROS and NINETY-TWO CENTS

, 7th June 2017.

3. SAGUNTO

The definition of the budget for Sagunto's case study takes into account part of improvement 1 and improvement 2 from Port Sagunt described in section 4.2, whereas there is no budget for Sagunto City Centre and North Palancia for reasons that will be explained later on. The part of improvement 1 that has been included in the budget is the installation of the general PRV that is placed upstream the city and affects/regulates the pressure for the whole network downstream. And improvement 2 includes the installation of a couple of pressure reducing valves at the entrance of a group of districts metering areas (DMAs). As commented for Teruel, before the installation of these valves it is obvious that the division of the network into these DMAs is needed, but since this is not a civil work project, only the budget for the commented improvements are discussed.

For the installation of the valves, there are three distinguishable phases that will apply to each of the valves in each of the different districts considered:

1. Earthworks: This accounts for the trial pit opening for the construction of the water chamber where the valve will be placed
2. Mechanical and civil works: This activity considers the construction of the water chamber itself and the installation of the different elements and pieces that conform a typical pressure reducing valve installation. It must be noted that the price of the elements already includes the necessary civil works as well as the installation and transport of the element. The technical explanation for the choice of the different elements depicted in the budget is not described.
3. Finish: The replenishment of the pavement after ground works are done is needed and an overall estimated price for these kind of works is depicted in this activity.

The diameter election is a function of the existing pipeline in the network however, the exact location of the water chamber has not been studied and therefore, the situation of the ground conditions, accessibility, etc. cannot be accounted for, with the discrepancies this may cause in a real budget scenario. Nevertheless, exact real conditions can never be reflected and that is why job overheads are contemplated in budgets.

Only two additional gate valves are included that do not need the above-mentioned steps in order to install them. These two gate valves (DMA 4 and DMA 6) are needed in order to separate DMA 4 from DMA 5 and DMA 6 from DMA 7 (refer to Figure 4-6). Although the whole division of the network is not budgeted as commented before, these two valves are indeed necessary in order to be able to apply improvement 2 consisting of the installation of two PRVs to a group of DMAs and therefore, they must be isolated between them. Additionally, only the price of the valve itself (including installation) is depicted since the water chamber is supposed existing already and there is no need to construct it.

With all the previously described, the budget layout has been followed for all the different DMAs pressure reducing valves installation.

The total cost of the improvement is reflected in the budget summary, at the end of the budget break down.

This cost represents a total amount of 28,046.56€ before profit and jobs overhead and 30,851.22€ before taxes, price that will be considered for analysis.

To make a cost-benefit analysis, Table 4-4 is used. From the table, the energy savings expected from improvement 1 and 2 are 10,622 kWh/month. With an approximate unit price of energy of 0.1€/kWh, there is an annual saving of 12,746€. This results in a return of investment (ROI) of:

$$ROI = \frac{Initial\ investment\ (€)}{Anual\ savings\ (€/year)} = \frac{30{,}851.22}{12{,}746} = 2.4\ years$$

The same remarks regarding the energy savings value can be done as in Teruel's budget. All the indirect cost savings are not accounted in the annual savings but just the energy reduction.

Referring to water savings, the results are much more revealing with a total water reduction of 34,696 m^3 per month or 416,352 m^3 annually. With the same water price value, the monetary savings would amount to 260,220€, a non-neglectable figure at all. But again, considering energy efficiency figures only, this value is not used for returns on investment's calculations.

So, as a rough analysis of cost-benefit study, the previous datum will be used.

Either way, the total investment calculated for the works described fall within complete acceptable and affordable values for this kind of works, and the recovery period is also very acceptable.

Regarding Sagunto City Centre improvements, and as it has already been commented, the division of the network into DMAs is already a reality. Improvement number 2, the installation of the PRV at the entrance of North Palancia has no significant impact, and finally, improvement 3 is to be performed. But this measure implies no investment at all since the valves are already under operation. Therefore, this is an operational measure as it has been described in the paper. By reducing the pressure set point of the PRVs there will be energy savings as per Table 4-6. It makes no sense to study the ROI value for this measurement but it is interesting to mention that the economic investment might be focused more on awareness campaigns rather than in infrastructure so that a pressure reduction in the service pressure in the network does not provoke societal rejection.

ESTIMATE AND TAKE-OFF LINES

CODE	DESCRIPTION	UNITS	LENGTH	WIDTH	HEIGHT	QUANTITY	PRICE	AMOUNT
01	**DMA 4**							
01.01	**Mechanical and Civil Works**							
01.01.01	**UD GATE VALVE. E.L. ø 150 PN-10**							
						1.00	218.66	218.66
	TOTAL 01.01							**218.66**
	TOTAL 01							**218.66**
02	**DMA 6**							
02.01	**Mechanical and Civil Works**							
02.01.01	**UD GATE VALVE. E.L. ø 150 PN-10**							
						1.00	218.66	218.66
	TOTAL 02.01							**218.66**
	TOTAL 02							**218.66**

ESTIMATE AND TAKE-OFF LINES

CODE	DESCRIPTION	UNITS	LENGTH	WIDTH	HEIGHT	QUANTITY	PRICE	AMOUNT
03	**DMA P1, P2, P3, P4, P11b**							
03.01	**Earthworks**							
03.01.01	**M2 PAVEMENT DEMOLITION 15 CM**							
Act0010			2.80	2.30		6.44		
						6.44	10.74	69.17
03.01.02	**m³ TRIAL PIT LOOSE SOIL STREET CHAMBER**							
Act0010		1	2.50	2.00	1.80	9.00		
						9.00	3.51	31.59
	TOTAL 03.01							**100.76**
03.02	**Mechanical and Civil Works**							
03.02.01	**GATE VALVE DN=200 mm**							
Act0010		2				2.00		
						2.00	789.14	1,578.28
03.02.02	**ud GATE VALVE DN=80 mm**							
Act0010		2				2.00		
						2.00	472.24	944.48
03.02.03	**ud PRESSURE REDUCING VALVE**							
Act0010		1				1.00		
						1.00	4,238.08	4,238.08
03.02.04	**UD BEND 90º HºFº ø 80 F.F.**							
Act0010		2				2.00		
						2.00	45.73	91.46
03.02.05	**UD TEE Hº Fº ø 200/80 F.F.F.**							
Act0010		2				2.00		
						2.00	62.95	125.90
03.02.06	**UD REDUCT. Hº Fº ø 300/200 F.F.**							
Act0010		2				2.00		
						2.00	200.00	400.00
03.02.07	**UD PIPE DISMANTLING JOINT HºFº ø200x200 F.F.**							
						1.00	45.35	45.35
03.02.08	**UD AIR VENT T.F. ø 80 PN-10**							
						1.00	527.61	527.61
	TOTAL 03.02							**7,951.16**
03.03	**Finish**							
03.03.01	**m² PAVEMENT M.B.C. TYPE D-12 6 CM.**							
Act0010			2.80	2.30		6.44		
						6.44	25.82	166.28
	TOTAL 03.03							**166.28**
	TOTAL 03							**8,218.20**

ESTIMATE AND TAKE-OFF LINES

CODE	DESCRIPTION	UNITS	LENGTH	WIDTH	HEIGHT	QUANTITY	PRICE	AMOUNT
04	**DMA P5, P7, P8**							
04.01	**Earthworks**							
04.01.01	**M2 PAVEMENT DEMOLITION 15 CM**							
Act0010			2.80	2.30		6.44		
						6.44	10.74	69.17
04.01.02	**m³ TRIAL PIT LOOSE SOIL STREET CHAMBER**							
Act0010		1	2.50	2.00	1.80	9.00		
						9.00	3.51	31.59
	TOTAL 04.01							**100.76**
04.02	**Mechanical and Civil Works**							
04.02.01	**GATE VALVE DN=200 mm**							
Act0010		2				2.00		
						2.00	789.14	1,578.28
04.02.02	**ud GATE VALVE DN=80 mm**							
Act0010		2				2.00		
						2.00	472.24	944.48
04.02.03	**ud PRESSURE REDUCING VALVE**							
Act0010		1				1.00		
						1.00	4,238.08	4,238.08
04.02.04	**UD BEND 90º HºFº ø 80 F.F.**							
Act0010		2				2.00		
						2.00	45.73	91.46
04.02.05	**UD TEE Hº Fº ø 200/80 F.F.F.**							
Act0010		2				2.00		
						2.00	62.95	125.90
04.02.06	**UD REDUCT. Hº Fº ø 300/200 F.F.**							
Act0010		2				2.00		
						2.00	200.00	400.00
04.02.07	**UD PIPE DISMANTLING JOINT HºFº ø200x200 F.F.**							
						1.00	45.35	45.35
04.02.08	**UD AIR VENT T.F. ø 80 PN-10**							
						1.00	527.61	527.61
	TOTAL 04.02							**7,951.16**
04.03	**Finish**							
04.03.01	**m² PAVEMENT M.B.C. TYPE D-12 6 CM.**							
Act0010			2.80	2.30		6.44		
						6.44	25.82	166.28
	TOTAL 04.03							**166.28**
	TOTAL 04							**8,218.20**

ESTIMATE AND TAKE-OFF LINES

CODE	DESCRIPTION	UNITS	LENGTH	WIDTH	HEIGHT	QUANTITY	PRICE	AMOUNT
05	**DMA Global**							
05.01	**Earthworks**							
05.01.01	**M2 PAVEMENT DEMOLITION 15 CM**							
Act0010			5.26	1.60		8.42		
						8.42	10.74	90.43
05.01.02	**m³ TRIAL PIT LOOSE SOIL STREET CHAMBER**							
Act0010		1	5.26	2.00	1.90	19.99		
						19.99	3.51	70.16
	TOTAL 05.01							**160.59**
05.02	**Mechanical and Civil Works**							
05.02.01	**GATE VALVE DN=300 mm**							
Act0010		2				2.00		
						2.00	1,058.39	2,116.78
05.02.02	**ud GATE VALVE DN=80 mm**							
Act0010		2				2.00		
						2.00	472.24	944.48
05.02.03	**ud PRESSURE REDUCING VALVE**							
Act0010		1				1.00		
						1.00	4,799.68	4,799.68
05.02.04	**UD BEND 90º HºFº ø 80 F.F.**							
Act0010		2				2.00		
						2.00	45.73	91.46
05.02.05	**UD TEE Hº Fº ø 300/80 F.F.F.**							
Act0010		2				2.00		
						2.00	500.86	1,001.72
05.02.07	**UD PIPE DISMANTLING JOINT HºFº ø300x200 F.F.**							
						1.00	189.59	189.59
05.02.08	**UD AIR VENT T.F. ø 80 PN-10**							
						1.00	527.61	527.61
05.02.06	**UD REDUCT. Hº Fº ø 500/300 F.F.**							
Act0010		2				2.00		
						2.00	534.65	1,069.30
	TOTAL 05.02							**10,740.62**
05.03	**Finish**							
05.03.01	**m² PAVEMENT M.B.C. TYPE D-12 6 CM.**							
Act0010			5.26	2.00		10.52		
						10.52	25.82	271.63
	TOTAL 05.03							**271.63**
	TOTAL 05							**11,172.84**
	TOTAL							**28,046.56**

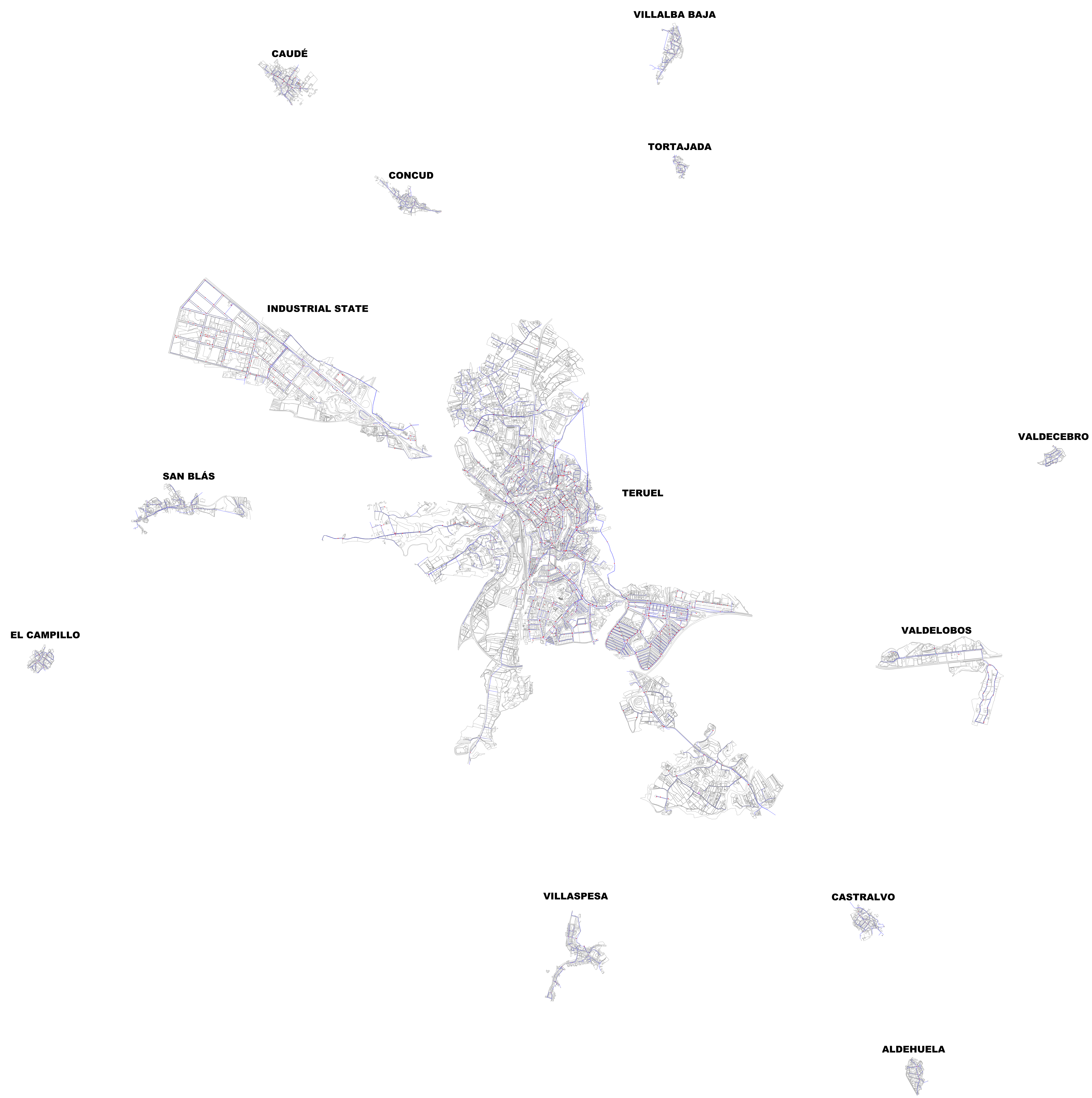
ESTIMATE SUMMARY

CODE	DESCRIPTION	AMOUNT	%
01	DMA 4	218.66	0.78
02	DMA 6	218.66	0.78
03	DMA P1, P2, P3, P4, P11b	8,218.20	29.30
04	DMA P5, P7, P8	8,218.20	29.30
05	DMA Global	11,172.84	39.84
	DIRECT + JOBSITE OVERHEAD	**28,046.56**	
	10.00 % Home overhead and profit.......	2,804.66	
	ESTIMATE BEFORE IVA	**30,851.22**	
	21% IVA..................................	6,478.76	
	ESTIMATE	**37,329.98**	

This estimate is THIRTY-SEVEN THOUSAND THREE HUNDRED TWENTY-NINE and NINETY-EIGHT CENTS

, 7th June 2017.

DRAWINGS



TRABAJO FIN DE MÁSTER EN INGENIERÍA INDUSTRIAL

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

ESCUELA TÉCNICA SUPERIOR INGENIEROS INDUSTRIALES VALENCIA

Project:
COMPARATIVE STUDY OF THE ENERGY EFFICIENCY IN PRESSURIZED WATER TRANSPORT SYSTEMS

Date: July 2017

Scale: 1/25.000

Drawing: General layout of the potable water network of Teruel

Nº Drawing: 1

MARIANO AGUDO BLANCO
Author

TRABAJO FIN DE MÁSTER EN INGENIERÍA INDUSTRIAL

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

ESCUELA TÉCNICA SUPERIOR INGENIEROS INDUSTRIALES VALENCIA

Project: COMPARATIVE STUDY OF THE ENERGY EFFICIENCY IN PRESSURIZED WATER TRANSPORT SYSTEMS

Date: July 2017

Scale: 1/5.000

Drawing: General layout of the potable water network of Teruel

Nº Drawing: 2

MARIANO AGUDO BLANCO
Author

TRABAJO FIN DE MÁSTER EN INGENIERÍA INDUSTRIAL

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

ESCUELA TÉCNICA SUPERIOR INGENIEROS INDUSTRIALES VALENCIA

MARIANO AGUDO BLANCO
Author

Project:
COMPARATIVE STUDY OF THE ENERGY EFFICIENCY IN PRESSURIZED WATER TRANSPORT SYSTEMS

Date:
July 2017

Scale:
1/5.000

Drawing:
General layout of the potable water network of Teruel

Nº Drawing:
3

TRABAJO FIN DE MÁSTER EN INGENIERÍA INDUSTRIAL

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

ESCUELA TÉCNICA SUPERIOR INGENIEROS INDUSTRIALES VALENCIA

MARIANO AGUDO BLANCO

Author

Project:

COMPARATIVE STUDY OF THE ENERGY EFFICIENCY IN PRESSURIZED WATER TRANSPORT SYSTEMS

Date:

July 2017

Scale:

1/10.000

Drawing:

General layout of the potable water network of Sagunto

Nº Drawing:

4

TRABAJO FIN DE MÁSTER EN INGENIERÍA INDUSTRIAL

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

ESCUELA TÉCNICA SUPERIOR INGENIEROS INDUSTRIALES VALENCIA

MARIANO AGUDO BLANCO
Author

Project:
COMPARATIVE STUDY OF THE ENERGY EFFICIENCY IN PRESSURIZED WATER TRANSPORT SYSTEMS

Date: July 2017

Scale: 1/5.000

Drawing: General layout of the potable water network of Sagunto center and North Palancia

Nº Drawing: 5

TRABAJO FIN DE MÁSTER EN INGENIERÍA INDUSTRIAL

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

ESCUELA TÉCNICA SUPERIOR INGENIEROS INDUSTRIALES VALENCIA

MARIANO AGUDO BLANCO
Author

Project:
COMPARATIVE STUDY OF THE ENERGY EFFICIENCY IN PRESSURIZED WATER TRANSPORT SYSTEMS

Date:	Scale:
July 2017	1/5.000

Drawing:	Nº Drawing:
General layout of the potable water network of Port Sagunt	6