Smart Water-Energy Management Using Digital Twin in Water Distribution Systems

Case Study of Santa Cruz Water Supply and Distribution System

Ana Micaela Teodoro Antunes Rolla

Thesis to obtain the Master of Science Degree in

Civil Engineering

Supervisor:

Prof. Helena Margarida Machado da Silva Ramos

Examination Commitee:

Chairperson: Prof. Rodrigo De Almada Cardoso Proença de Oliveira

Supervisor: Prof. Helena Margarida Machado da Silva Ramos

Members of the Committee: Prof. Modesto Pérez Sánchez

May 2022

Declaration

I declare that this document is an original work of my own and that it fulfills all requirements of the Code of Conduct and Best Practices of the University of Lisbon.

Acknowledgements

First of all, I would like to express my gratitude to Engineer Rui Silva Santos for all the provided help in the development of this work, all the support and the opportunity to contribute to such an important project with such a relevant impact in the future of Santa Cruz Municipality.

I would also like to thank Professor Helena Ramos, for all the support, persistency, availability, guidance on the writing, structure and development of the thesis, and without whom this work would never come to an end.

Also a word of gratitude to the best friends I could ask for, for the constant motivation and support, and for doing everything they can to help.

Finally, an enormous thanks to my family, my parents, my brothers and my boyfriend, who always stay by my side, support me, and make sure that I have everything to get through every step of my life and follow my dreams.

Abstract

One of the problems contributing to water scarcity are water losses existing in Water Supply Systems (WSS) and Water Distribution Systems (WDS), originated mainly by excess of pressures and bad network management. Due to the reduced investment made over the years by the responsible management entities, water systems don't keep pace with population growth and its consequent increased consumption.

One way of reaching better energy efficiency in the network is by replacing Control Valves (CV) by Pumps working as Turbines (PAT), allowing the conversion of excess pressure in electric power.

Digital twins appear as a virtual representation of the physical networks, integrating virtual engineering models with city-scale reality models and Geographic Information Systems (GIS) data. This technology provides accurate and reliable data that utilities can use to perform analysis throughout their water systems.

In this work, after a pressure reduction strategy implementation, the implantation of a Pumps working as Turbine (PAT) upstream of an existing reservoir was studied, achieving the same performance as the designed Flow Control Valve (FCV) complementing its functions with renewable energy production.

The study demonstrates that if these projects are implemented, a large amount of water and energy will be saved, resulting in a 3,3M m3 of water and more than 1M of kWh corresponding to 1.5M € saved every year, and also more than 530ton/year of CO_2 emissions would be avoided.

Key-Words: Excess Pressures; Digital Twins; Water Savings, Renewable Energy, Pumps working as Turbines(PAT)

Resumo

Um dos problemas que contribuem para a escassez de água são as perdas que se verificam nos sistemas de abastecimento e de distribuição de água, perdas essas causadas, entre outros fatores, por níveis de pressões excessivos. Devido ao baixo investimento levado a cabo pelas entidades gestoras, os sistemas por si geridos não acompanham o crescimento populacionais e as consequentes solicitações.

Uma forma de atingir uma melhor eficiência energética dos sistemas é utilizando Bombas a funcionar como turbinas (BAT) de forma a produzirem energia renovável a partir de quantidades dissipados por válvulas.

Os modelos hidráulicos digitais surgem como uma representação virtual dos modelos existentes fisicamente. Este tipo de tecnologia permite a obtenção de resultados com um elevado nível de confiança permitindo a execução de testes e simulações virtuais da rede hidráulica.

Neste trabalho, após um estudo com o objetivo de reduzir as pressões no sistema, foi estudada a implementação de uma BAT a montante de um reservatório existente, acabando por atingir o mesmo desempenho que a válvula reguladora de caudal (VRQ) previamente dimensionada, mas com a vantagem de produzir energia renovável.

Este estudo demostra que se o projeto for implementado, volumes significativos de água, energia e emissões de CO2 serão poupados anualmente, nomeadamente cerca de 3,3M m3 de água e mais de 1 milhão de kWh por ano correspondentes a mais de 1.5M €, e ainda mais de 530ton/ano de emissões de CO_2 evitadas.

Palavras-Chave: Pressões Excessivas, Modelos Hidráulicos Digitais, Poupança de Água, Energia Renovável, Bombas-Turbina(BT)

TABLE OF CONTENTS

List of Figures

List of Tables

Abreviations and Simbols

AL – Apparent Losses

ALC - Active Losses Control

AMI – Advanced Metered Infrastructures

ARM – Água e Resíduos da Madeira / Water and Wastewater Madeira Management Entity

BGRI - Base Geográfica de Referenciação de Informação - Geographic Referenced Information Database

CARL – Current Annual Real Losses

CMMS - Computerized Maintenance Management System

DMA – District Metered Areas

DT – Digital Twin

EL – Electric Regulation

ERSAR – Entidade Reguladora dos Seviços de Águas e Reíduos - Water and Waste Water Regulatory Entity

ERSE - Entidade Reguladora dos Serviços Energéticos - Energetic Services Regulatory Entity

GIS - Geographic Information Systems

HER – Hydraulic and Electric Regulation

HR – Hydraulic Regulation

IA – Influence Area

ICT - Information and Communications Technologies

IEA – International Energy Association

ILI - Infrastructure Leakage Index

FCV – Flow Control Valve

ILI – Infrastructure Leakage Index

INE - Instituto Nacional de Estatística - Portuguese Statistical Institute

IWA – International Water Association

MSC – Municipality of Santa Cruz

PEAASAR - Portuguese Supply and Residual Water Strategic Plan

PI – Performance Indicators

PRV – Pressure Reducing Valve

RL – Real Losses

SCADA - Supervisory control and data acquisition

SWG – Smart Water Grid

UAC – Unbilled Authorized Consumption

UARL – Unavoidable Annual Real Losses

VOC – Variable Operation COnditions

WB – Water Balance

WDS – Water Distribution System

WSS – Water Supply System

WWAP – World Water Assessment Program

1. INTRODUCTION

1.1 Scope

Water is an increasingly scarce and unreplaceable resource that must be preserved, and even though its abundancy in our planet, there is a really low percentage of it that can be effectively available for all different usages, reason why it must be carefully managed [1][3].

One of the contributive problems to water scarcity are water losses existing in Water Supply and Distribution Systems, originated mainly by excess of pressures and bad network management. Taking this subject as a starting point, this work aims to analyze an existing hydraulic system that not only has a significant value of water losses but also, due to population growth, local development and natural morphology, its hydraulic system does not work in proper conditions. Thus, from a perspective of sustainable and integrated management of water resources in a context of climate change, it is essential to increase the levels of efficiency in the structures through the reformulation and rehabilitation of obsolete systems, alteration of network management behavior, so that water losses do not continue to increase almost uncontrollably, putting the future at risk, since they are at an unsustainable economically and environmentally level and, if nothing is done, there will be no water to the municipality supply. [1]-[4].

Climatic changes and scarcity of natural resources allied with the increasing of population and its consumption led to an urgent need of management strategies improvement. In this context, one of the main causes of water leakage in water supply and distribution systems is a bad pressure management. For this purpose, PRV and FCV are usually introduced in strategical locations of water systems, to control and reduce existing pressures. [1]-[4].

In parallel with water consumption increase it is energy consumption, due to an interconnection existing between these two resources, in which the exploitation of one implies the consumption of the other and vice-versa. For this reason, sources of green energy production must be developed to follow the existing increasing needs. In WSS and WDS it is possible to produce renewable energy, taking advantage of the regulating devices operation conditions and, instead of dissipating energy, implementing PAT solutions, that energy will be recovered. PAT solutions were the chosen turbines because they appeared as a cheaper alternative to conventional turbines with reasonable efficiency levels [1]-[4].

In addition to water savings and management, other subjects that must take everyone’s attention is climatic changes and, consequently, CO2 emissions and green and clean energy production. In the present case, a case-study will be analyzed once it has energy dissipating devices implemented to regulate pressures in hydraulic systems and they can be complemented with energy recovering devices, with significantly low costs associated. [1]-[4].

1.2 Objectives

The present work aims to study an existing Hydraulic system located in Santa Cruz, a municipality in the Portuguese Island Madeira. Currently, more than 80% of the water entering the system doesn't get to the final consumer, meaning it is lost somewhere along its way, reason why strategies must be urgently considered and applied by the Management entities. One aspect, apparently of minor importance, but which has certainly also contributed to the current state of Madeira water network, is the existing myth that Madeira's water resources are practically inexhaustible. This is not true. Not only resources are not infinite, but there is also no more room for waste. Maintaining the continued mistakes of the past, without an urgent change management strategy will lead to sotution without enough water to supply all Santa Cruz Population.

The creation of a digital twin hydraulic model will be performed, being this a very useful management tool that allows the study of different variables such as pressures, operating devices, velocities and headloss values occurring in real time. The greatest amount of information fed into the model, the greater results, predictions, and analysis could be performed.

This hydraulic model development will be described through a pilot-zone, being all the data and referred development happened during the study of leakage reduction carried out by the Hydraulic Engineering company RSS which allowed the creation of not only an accurate twin of the existing network but also a second one with modifications improving significantly the system's hydraulic behaviour.

After the model development the installation of an hidropower plant will be performed to analyse the possibility of producing renewable energy taking advantage of a location where energy dissipation is occurring.

1.3 Structure of the document

This thesis is divided in 6 main chapters, starting with the Introduction previously presented as Chapter 1.

Chapter 2 approaches in a generalistic way the several problems in water systems such as energy and water wasted resources, management strategies, including the interdependency of water an energy matters, the possibility of energy recovery in water supply systems and economical viability indicators that should be considered when an investment in different solutions is intended.

Chapter 3 develops the digital twin concept explaining its features and describing some of these technologies and its benefits. It's also explained in this chapter management technologies and how it can be a useful tool to management entities.

The practical case-study where all the previously described concepts are applied is exposed in Chapter 4, being developed two digital twin models, one of a real water network and a second one with some changes proposed by Hydraulic Engineering company RSS, to improve the system's hydraulic behaviour. Chapter 4 last sub-chapters analyse the feasibility of a renewable energy solution.

In Chapter 5 it will be analysed economically all the changes previously mentioned and it will also be attended the relevance of each component in the overall system study.

Finally, Chapter 6 aims to summarize all the information, taking some conclusions to the considered approximations and the obtained results.

2. WATER AND ENERGY LOSSES

2.1 Introduction

Being water an unreplaceable resource for life, its correct management becomes extremely important. Despite its abundance on our planet, much of the water is not in a state conducive to its use by the human being. Of all the existing water on the planet, about 97.5% is salty, and of the apparent 2.5% possible to be used, more than half (68.7%) are in the form of ice and snow and 29.5% in underground locations, being possible to use only 0.26% of the existing water on the planet, located in lakes, bats and rivers [1].

Due to the reduced investment made over the years by the responsible management entities, water systems are now aged and its infrastructure are overloaded. Water networks operate beyond their useful life, not keeping pace with population growth and its consequent increased consumption, causing supply failures and excessive water losses in systems, shown through ruptures and leaks from pipelines and reservoir overflows. The efficiency of the systems is already beginning to be a concern of the management entities and it should be seen as opportunities to improve the management of these systems [1].

2.2 Water Balance

As water is an indispensable asset to life, but increasingly scarce, it is essential to preserve it and avoid its waste. The evolution of the annual water volume wasted in water distribution systems (WDS) is itself an indicator that allows to verify the evolution of the system's efficiency over the years. This value should be measured and reduced as much as possible until it reaches a minimum level, from what lower values imply an investment which is no longer economically viable [4].

To be able to analyze the water losses of a system, it is important to be aware of the various components of the Water Balance (WB), a methodology developed *by the International Water Association* (IWA) that divides system input volume into several components, according do Fig. 1 [4].

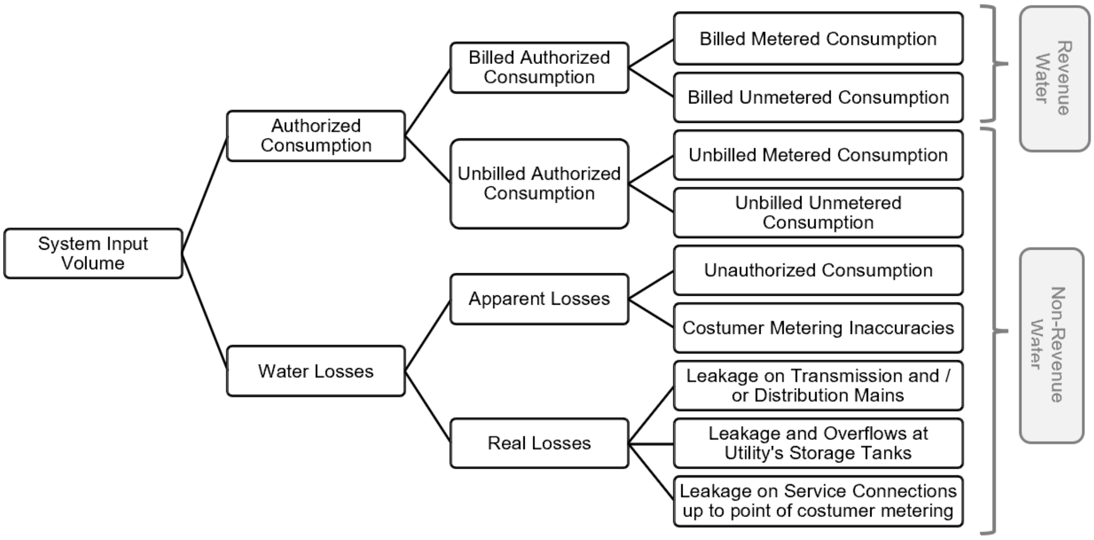

Fig. 1 – Water Balance Components [4].

Water losses are defined as the difference between the volume of water entered in the system and the authorized consumption. Authorized consumption is the volume of water consumed by consumers, including domestic, commercial, and industrial purposes. Authorized consumption can be billed or unbilled by the managing entity, being some examples of this last component the following: firefighting, street cleaning and irrigation of municipal gardens. Water losses are reflected in the volume of water that does not reach the consumer, meaning that after entering the system it ends up being lost, without any associated billing. This component is divided in Apparent Losses (AL) and Real Losses (RL). The first one includes water volumes of unauthorized consumptions and flow meter devices measurement errors, ending up, consequently, unbilled by the management entity, like illicit consumption or theft, and also the measurement errors associated with the existing elements in the distribution network. On the other hand, the second one includes the volumes of water resulting from tank's overflows, leaks or ruptures occurring along the network [4][6].

The components of the Water Balance should be measured, analyzed and, in the end, considered as possible indicators [7]

Since the volume of water lost in the system is directly reflected in the Real Losses component, IWA proposes a set of Performance Indicators (PI) of this component, like the volume of losses presented as a percentage of the volume of water entered in the system. This indicator has some limitations and must be used carefully since the variability of consumption affect this component when presented in a percentage value. Also, most of the actual losses occur in the connection extensions, meaning that the parameter in the network should be analyzed according to its extension and quantity of connections per area [6]-[8].

Another indicator that should be analyzed is Unavoidable Annual Real Losses (UARL). This indicator allows the recognition of different components of Real Losses in the system as the extension of the network and connections, taking also into account the average pressure of the network in its determination.

Unavoidable Annual Real Losses (UARL) is an indicator that can be obtained through equation [1]:

$$UARL\ (l/connection/day) = (18\ Ld + 0.80\ Nr + 25\ Lr)\ x\ P \qquad [1]$$

where *Ld* represents water distribution system's length in km, *Lr* the connections' total length between property limit and the flow meter, in km, Nr is the number of connections existing in the network and P represents average pressure in the network.

The difference between Current Annual Real Losses (CARL) and Unavoidable Annual Real Losses (UARL) of a system represents the real losses reduction potential, being the quotient between those two variables called Infrastructure Leakage Index (ILI), a non-dimensional variable that shows the state of the network. Well-managed systems should have an ILI value close to one, meaning that the higher the result obtained, the older and in worse conditions the system is. UARL represents the minimum real losses value that can be achieved in a WDS, lower values will imply costs higher than the economic value of the water saved. [6]-[8].

2.3 Pressure Management

Water losses in a water distribution system are directly reflected in economic losses since, in addition to the wasted natural resource, there is still all the associated treatment and transport. Thus, by decreasing the volume of water lost, pumping energy and chemicals responsible for its treatment and transport would decrease, reflecting significant costs. Loss reduction in a system should be supplemented with Active Loss Control (ALC) methods to locate and mitigate existing leaks. Of the various loss components, the Real Losses have the highest expression (mainly reflected in ruptures and other small leaks existing in the distribution network), and there are several factors that are at their origin, namely the age and state of conservation of the pipelines, the characteristics and use of the surrounding land, fragile connections and excessive pressures. One of the most influential factors in water losses is the excess pressure, and, in some case-studies where volume of water was measured during periods with no consumption, it was found that there was a direct relationship between average pressure in the distribution network and the volume of water losses. Thus, the pressure in the network is one of the elements to be managed when a reduction of water losses in the system is intended, minimum and maximum values must be ensured so as not to cause absence of water or discomfort in users [9][10].

Pressure in a WDS can be reduced and controlled through some equipment installation as Pressure Reducing Valves (PRV) and Flow Control Valves (FCV), in strategical locations coordinating its installation with the management of existing ones and replacement of used pipes, in order to promote a good hydraulic systems' behaviour and management [10][11].

Pressure Reducing Valves are usually installed in the systems to control pressure or head, causing dissipation of energy. This devices can operate in three ways: by locking when the downstream pressure is higher than the value configured in the valve, increasing the headloss until it reaches the stablished value; if downstream pressure is lower than stablished, the valve will open, reducing the headloss; and the valve will be closed in case of a downstream pressure higher than upstream pressure [2].

The dissipated energy caused by the management of this devices could be recovered if, for the same purpose, it would be used turbines instead of PRV, improving the sustainability of the water system [12] [13].

2.4 Active Leakage Control and District Metered Areas (DMA)

Active Leakage Control (ALC) consists of a set of measures to locate and repair existing leaks and ruptures in water distribution systems, being a prevention practice avoiding unforeseen work of damaged areas due to ruptures and reducing the volume of water losses in the systems. Because they require constant monitoring, several authors recommend that ALC measures should be considered with the creation of District Metered Areas (DMA), being easier to identify the areas with higher volume of water losses and locate the priority pipes to repair. The sectorization of the network allows more detailed monitoring and control of the system, the water losses evolution over the time and the areas with the highest volume of losses and, consequently, with the greatest need for implementation of ALC measures [10][11][14]-[16].

Data from the different components of the water balance currently available are often estimated or even unavailable. Globally, consumptions and volume of water extracted from the sources of water resources have increased 1% per year, and this increase in consumption was expected to continue over the following years. However, the volume of water withdrawn appears to have stabilized which shows an improvement in the efficiency of the management of this resource [17].

Due to the increasing of climate changes consequences, management entities are forced to improve the management of water and energy lost in their systems, not only because of the natural resource but also the economic consequences. Some examples of methods currently used in leak detection are acquaphones, geophones and noise correlators, thermography, ground-penetrating radar, tracer-gas and video inspection [18].

2.5 Water-Energy Nexus

About 70% of the fresh water extracted for consumption globally is used in the irrigation sector, 20% in the industry sector and 10% in the domestic sector. Although the estimated water for energy supply is often included in the industry sector, the International Energy Agency (IEA) estimates that in 2010, the amount of water used in global energy production is about 75% of the water used in the industry sector, representing 15% of the total extracted water. Water and energy needs are expected to increase in all sectors about 30% by 2035 due to population growth. According to the World Water Assessment Program (WWAP), 20% of aquifers worldwide are over-exploited, with the extraction rate expected to increase by 1 to 2% annually [17].

To produce electricity, a large amount of water is required, for every step of energy production, as cooling steam, fuel extraction, or hydropower production. In another way, energy also needed to water operations, as pumping systems in WDS or treatment plants. The interdependency water-energy can also be dangerous because in an extreme situation the lack of one component will implicate a break in all process [19][20][21].

Water and energy are considered to be interconnected and interdependent, requiring a constant management, in order to follow the evolution of the planet. Global population is growing, needing more fresh water and electricity resources available once its demands are expected to increase, being important to optimize this resource, optimizing its use through recycling and producing energy from waste. In addition, climate changes are influencing the hydrological cycle, resulting extreme precipitation events as flooding and droughts, and consequent water storage issues [20]-[23].

2.6 Energy Recovery in Water Supply Systems (WSS)

Water Supply Systems (WSS), in there dissipation junctions, are a potential source of energy, being the knowledge of power availability a critical factor to understand de viability of converting energy dissipation into energy production. To dissipate excessive pressures in the network or to separate areas with different energy steps, Pressure reducing valves (PRVs) ore Flow Control Valves (FCV) are used. One way of reaching better energy efficiency in the network is by replacing Control Valves (CV) previously mentioned by Pumps working as Turbines (PAT), allowing the conversion of excess pressure in electric power [23].

To maximize the exploitation of a specific PAT, Variable Operation Strategy (VOS) concept was created, being achieved establishing an optimal speed regulation. Two different procedures were established for VOS: Hydraulic Regulation (HR) and Electrical Regulation (ER). In HR, Pressure Reducing Valve (PRV) is placed in series with the PAT imposing a head drop, and a Flow Control Valve (FCV) is placed in parallel bypassing a portion of the flow, allowing the PAT to work continuously in Best Efficient Point (BEP) but transforming only part of the energy into electrical energy. In Electrical Regulation (ER) an inverter is attached to the PAT enabling change of its rotational speed being all flow and energy converted. In this case, PAT can work out of its BEP. The combination of both modes is called Hydraulic and Electric Regulation (HER), increasing the efficiency and energy recovery potential of the system, as sown in Fig. 2 [23][24].

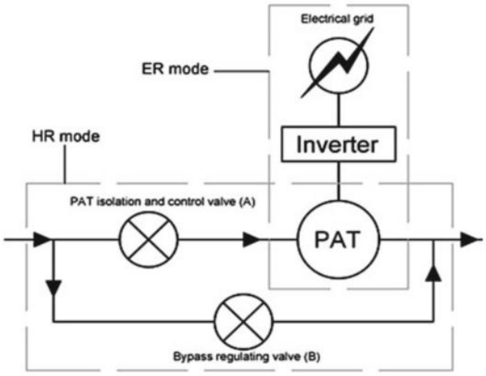

Fig. 2 - Installation scheme of a PAT in Hydraulic and Electric Regulation (HER) [23]

2.7 Economical Viability Indicators

In any project all the costs involved (such as capital costs, annual costs, exploitation costs, monetary), monetary fluxes and benefits mist be analyzed. Economical viability can be evaluated analyzing four parameters: Net Present Value (NPV), Benefit/Cost ratio (B/C), Internal Rate of Return (IRR) and Payback Period (T). [23]

NPV represents a balance of benefits and costs, and it can be calculated according to equation [2]

$$NPV = R - C - O - P \qquad [2]$$

Where C represents capital costs, O represents operational costs, R is revenues and P reposition costs.

Benefit/Cost Ratio relates the present value of benefits with total costs, through equation [3]

$$(B/C) = (R-O) / (C+P) \qquad [3]$$

Internal rate of return (IRR) is the discount rate that makes NPV equal to zero, the project with higher value of IRR will be the better one.

Finally, payback period (T) represents the number of years needed to recover the initial investment, being the cumulative number of years needed to reach positive cash flows.

3. SMART SYSTEMS

3.1 Introduction

The existence of the human being and its sustainable development have water, energy as fundamental pillars. Not only is water a necessary resource to produce, transport and use energy, but it is necessary for the extraction, treatment, distribution, retreatment and collection of energy, and these two resources are strongly interconnected. Predictable population growth and growing energy needs require excessive exploitation of existing water resources, overloading ecosystems and leaving scarce sources of natural resources, a factor further intensified by climate change that perpetuates the occurrence of extreme events more frequently and with greater intensity. The largest source of renewable energy production, covering 16% of the world's energy needs, is the production of hydropower energy, which, despite requiring the use of large amounts of water, is mostly returned to the river after the turbine pass through for energy production, and is later used for other purposes [17]-[24].

3.2 Smart Water Grid

Smart Cities can be defined as changed and more efficient networks and services due to digital solutions implementation benefitting inhabitants and businesses. In these way natural and energetic resources can have better management as well as the quality of life of resident and floating citizens can be increased. Considering the limitations of water, Smart Water Grids (SWG), as an integrated element of smart cities, are proposed as a new generation of water management considering the integration of information and communications technologies (ICT) as sensors, meters, digital controls and analytic tools, to automate, monitor and control the water network ensuring that water is delivered with good quality only when and where it is needed. When applied to the water industry, these ICT also provide automatic remote collection of data at site and wireless transmission being easier to analyze and improving system’s efficiency and quality [25]-[30].

A SWG requires a more efficient and complex implementation process and management strategy, compared to the conventional grids. The combination of sensors and communication network, putting together water-energy nexus, allow real-time monitoring, resources quality control, optimization of distribution and operations and to ensure reliability and customers safety [26].

The benefits of SWGs are the following [25]:

- Real-time monitoring asset condition: scheduling and planning for pipe main replacements and maintenance thanks to the data collected with advanced sensing technologies.
- Real-time pressure and water quality monitoring: sensors and flow meter data allow the control of hydraulic and water quality performances. Leaks can be located, and then minimizing the water losses and mitigating the pipe burst risk. Actuators, as automated

valves, respond to the affected areas preventing major damages, contamination of water or losses.

- Real-time water consumption information: smart water efficient gadgets provide real-time feedback on water demand achieving an optimum pumping and avoiding over or low pressures.

The SWG structure is based on two main platforms to establish the water management infrastructure: the water grid platform and the ICT [25]. The first one establishes the decentralization plan of the network, dividing the urban macro water grid into smaller ones, called meso-grids. Each meso-grid is formed with a fresh water source, a freshwater reservoir, a residential or industrial area and a treatment structure. In addition, there is a central management and a storage structure installed, so each meso-grid can be controlled individually or centrally. A bi-directional flow is stablished between freshwater reservoirs and central reservoir, allowing the management from one water grid to the other without altering the water cycle or disturbing the water demand (Fig. 3).

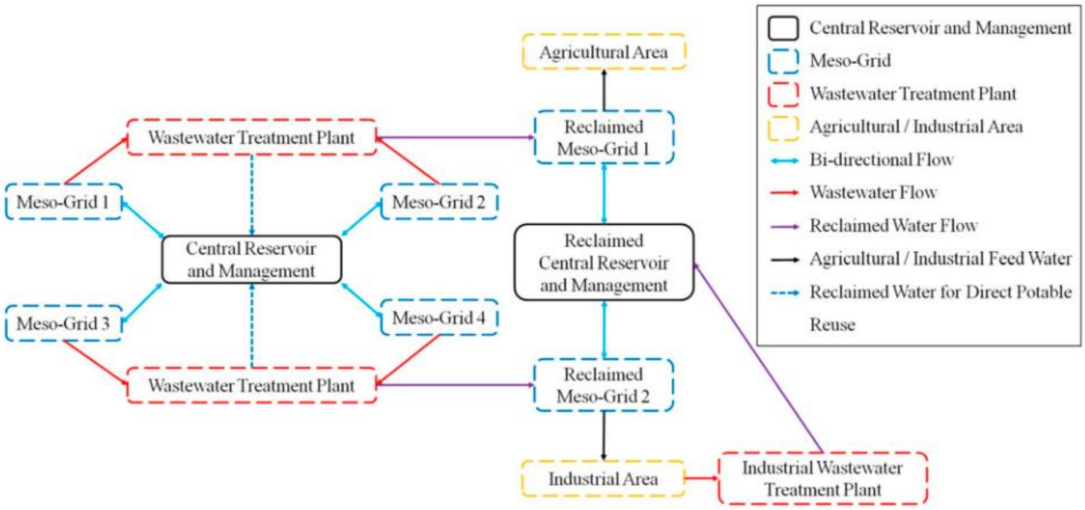

Fig. 3 - Water grid platform: fresh and reclaimed water cycles with zero water discharge [25]

The second one, is constructed on the main water grid platform to create an effective management structure between individual water network elements and the central management, enabling the data between them (Fig. 4). This is constructed to act in case of disturbance in individual grids when the central management must take over the control of the whole system. The ICT platform also combines the power and water grid data to increase efficiencies in all grids and to minimize the energy consumption [25].

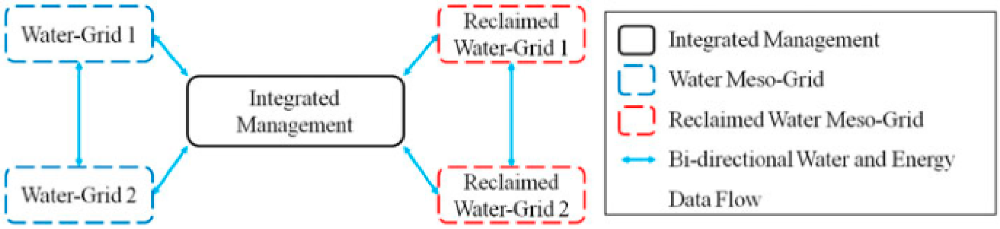

Fig. 4 - Integrated management structure of water grid platform [25]

In the future of the SWG there are different technologies that play an important role: Cyber-physical systems (CPSs), Digital Twins (DTs) and Blockchain. The two first, help in the general operation and management. The last one is essential for the change of business model and water utilities [27].

3.3 Smart Water-Energy Management

The fundamental concept of smart water management systems starts with a global balance, comparing water demand with water resources availability. Because of that, a general framework of the modeling system and a list with the necessary modules to cover it are essential.

Fig. 5 and Table 1 shows an example of a case study for a Smart Water Management System [25].

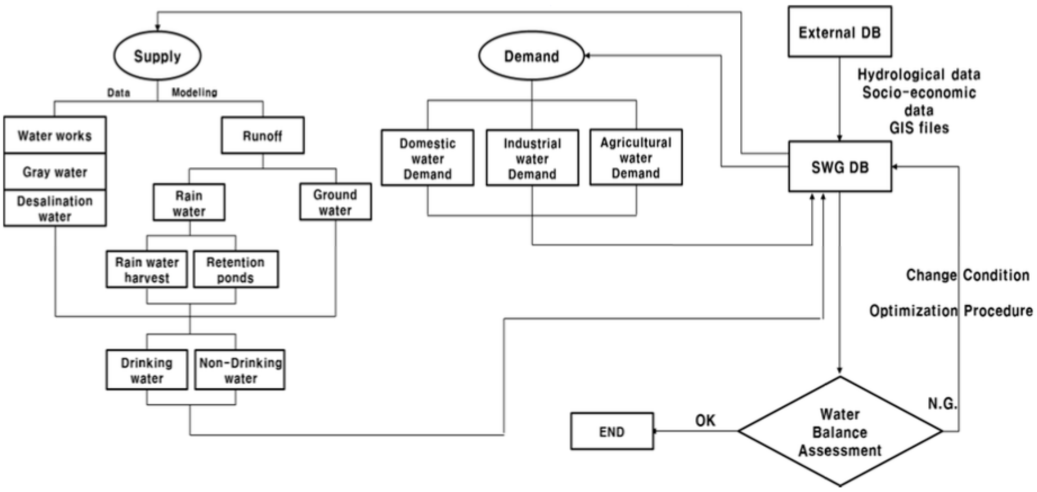

Fig. 5 - Overall framework of modelling for water balance assessment [25].

Table 1. Description of necessary modules [25]

Module	Named	Procedure
GIS interface	SWG-PP	Providing basic interface, GIS pre-processing, Projection and transformation
Rainfall-runoff	SWG-Runoff	Climate data management, Rainfall-runoff modeling
Channel flow	SWG-UDS	Routing channel, Open channel flow modeling(Sewer and river)
Water demand	SWG-Demand	Prediction of water demand(According to the scenario)
Water balance	SWG-WB	Water budget analysis, Predicting and quantifying water shortage

Smart water management is responsible for reduction of water losses and leakage, contributing to sustainability and self-sufficiency in water systems, and when followed by advanced information technologies, it results in different benefits, such as: better understanding of the water system, constant monitorization of water quality and behaviour, detecting leaks and controlling water losses more efficiently, reduction of financial losses, improvement of the system's efficiency and customer service reducing the water bill [25].

Real-time data collection, variable speed pumps, dynamic control valves and smart meters are essential elements to manage water and energy demand and achieve the benefits former listed. Moreover, having a hydraulic model representing all the scenarios of the water distribution system is also indispensable [25].

This system provides a water balance with the total water resources available and the total water demand. This is purely a quantity wise water balance that can occasionally provide the state of the water balance as sufficient, regardless of the water use [26].

3.3.1. Digital Water Features

Digital technologies help utilities becoming more resilient, innovative and efficient, offering unlimited potential to transform the world's water systems. Data exploitation value, automation and artificial intelligence (AI) allows water utilities to extend water resources, reduce non-revenue water and expand infrastructure life cycles [27].

Digital water concept is not seen as an option but as imperative since it can be integrated in every key point across the water cycle, from the physical infrastructure to the customer service, passing through the water quality. Water systems must be understood as smart grids, being a cyber-physical system made by sensors, processors and actuators that are constantly communicating with each other, and communicating all information into a control management system [27].

The concept is evolving into an open engagement ecosystem (Fig. 6) with digital inputs from across stakeholders both external to the utility and with other entities. Table 2 shows an overview of the Digital Water creation value [27].

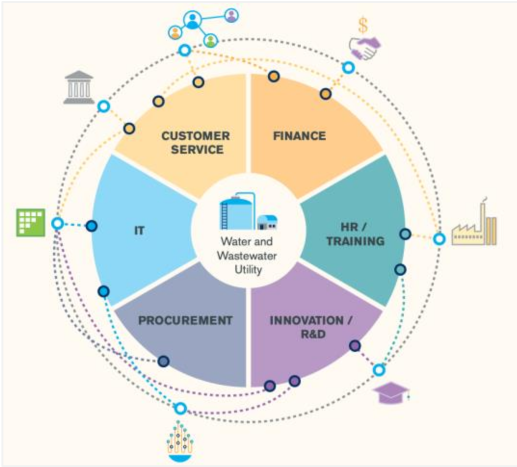

Fig. 6- Water and Wastewater utility concept [27]

Table 2. Digital water benefits [27]

Community Benefits	Operational Benefits
Increased Affordability - Rate structure with long-term affordability **Customer experience -** Reduced operational expenditure; Increased capital efficiency **Environmental protection -** Ensure minimal contamination and maximized conservation of water resources	**Process excellence -** Efficient data analysis and processing **Predictive Maintenance -** Reduced number of emergencies callouts; Reduced downtown of critical assets **Regulatory Compliance -** Reduced failures and overflows
Financial benefits	**Long-term Resiliency Benefits**
Reduced operational expenditure - Reduction in costs and risks associated to maintenance and energy operations **Increased capital efficiency -** Reduced costs from unexpected water main breaks **Increased revenue -** Value added digital services	**Increased resilience -** Improved operational flexibility **Workforce development -** Improved cross-department collaboration; Reduced safety risks **Brand and innovation -** Elevates utility brand and engagement in the water industry

3.3.2. Smart Water Management Technologies

3.3.2.1. Smart pipe and sensor

A Smart pipe prototype was designed as a module with monitoring capacity expandable for future available sensors. With several smart pipelines installed in critical sections of a public water system, real-time monitoring automatically detects flow rate, pressure, low-speed flow points, pipeline leaks and water quality without changing the operating conditions in the hydraulic circuit [28].

With the emergence of smart pipes and sensor networks, it is intended to manage demand and minimize leaks. The management of water resources means managing and ensuring that any system losses are minimal [28].

In this follow-up, one of the main issues in infrastructure monitoring is energy consumption and availability. The energy consumption recorded in the sensors should be optimized, keeping its functionality at an adequate level. Another issue in infrastructure monitoring, such as water pipeline networks, is data processing. The sensor node in these systems should be able to handle the locally produced data and then send the processed data to the control center in order to minimize the size of the necessary post processing and transmission data [29].

Individual sensor junctions usually have four main parts: data collection and processing unit, transmission unit, power management and sensors. The performance of each of these sections, in terms of power consumption and reliability, greatly affects the overall performance of the sensors and the network. Fig. 7 illustrates an overview of an intelligent pipe system wireless sensors network.

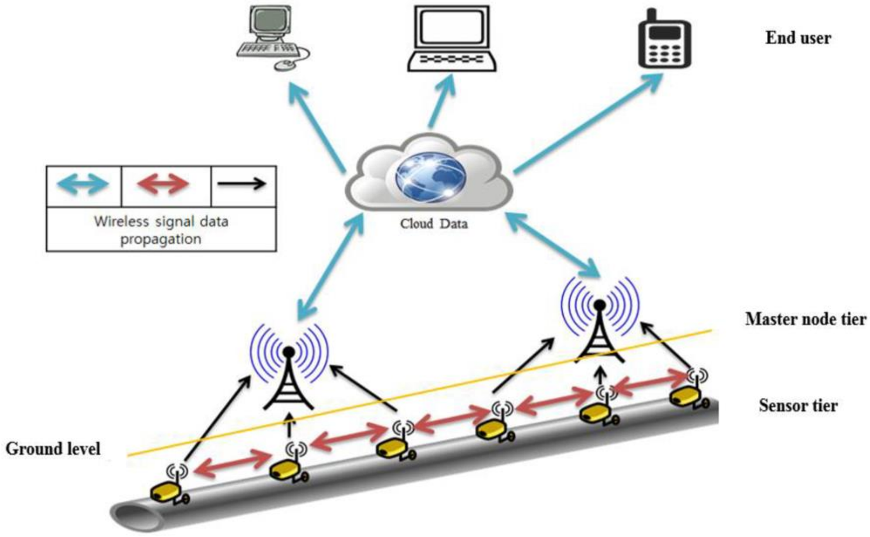

Fig. 7- Intelligent conduit and wireless sensor network [27]

To summarize, the smart wireless sensor network is a viable solution for monitoring the state of pressure and loss of water control in the system. The main advantage compared to other methods of water loss control is the continuous monitoring of the network without local operator intervention and with low energy consumption of the wireless sensor, allowing to remain operational for long periods [27].

3.3.2.2. Smart water metering

A water meter is a device used to measure the amount of water consumed by any consumer, while a smart water metering is also a measuring device having the complementary ability of store and transmit that data at a certain frequency. Therefore, while traditional water meters are read monthly or bimonthly and a water bill is generated from this manual meter reading, smart metering can be read from a distance and more frequently, providing instant access to water consumption information for customers and water supply network managers. These smart meters are a component of the Advanced Metering Infrastructure (AMI) (Fig. 8). With the implementation of this kind of technology in water systems, water management entities are improving hydraulic and energy efficiency, enabling leakage control as well as illegal connections in terms of water volumes[27][28].

Fig. 8- Automated meter infrastructure and Smart Water Metering [28]

On the other hand, with the use of smart meters, the water bill is associated with the volume consumed, instead of a fixed fee or a fee based on the size of the property. Individual metering, through Smart Water Metering, also allows for the introduction of increasing tariffs based on a differentiated volume of consumption to allow, firstly, for cross-subsidization of low-consumption customers by the largest consumers, and secondly, to encourage end customers to reduce their consumption of limited resources. [29]

Briefly, smart water metering essentially offers the opportunity to improve the balance between providing access to drinking water, the right of a management entity to receive payment for services rendered, as well as the joint responsibility of all to preserve scarce water resources [30]. It is a support tool to make real-time decisions based on registered database and helps to manage a better balance between satisfy demand and to increase the efficiency of Water distribution networks. To achieve it, a smart water meter includes the follow components: flow detection hardware, a transmitter and memory to store data and compensate for the disadvantages of traditional water meters.

3.4 Digital Twin for Water Distribution Systems

3.4.1. Digital Twin Concept

Digital twins appear as a virtual representation of the physical network, integrating virtual engineering models with city-scale reality models and Geographic Information Systems (GIS) data. Having the real physical data, digital twins are continuously updated with operational data from sensors, meters and other measuring devices, resulting in a model connected to digital infrastructure that supports smart water networks' management processes (i.e. planning, design, construction and operations). Digital twins provide accurate and reliable data that utilities can use to perform analysis throughout the lifecycle of a water system reproducing disruption scenarios for resilience assessment purposes, analyzing asset prognosis and health-status to determine proactive maintenance models [31] [32].

Digital Twins are used in water distribution system to solve distribution network management problems, from the design to the daily operations. The main capabilities of Digital Twins (DT) in the WDS are the following [33]:

- Optimal design of network elements with the goal of minimizing the overall carbon footprint and subject to quality-of-service constraints.
- Asset management to determine the optimal strategy for the renewal of the physical elements of the network and strategic operations.
- Model based leak detection and pre-location to reduce the leaks lifetime and reduce operational costs
- Determination of the optimal daily operation parameters, including water velocity, pressure and energy efficiency, among others.
- Early warning and informed response to emergencies to make quickly and effective decisions.
- Reproduce the network behavior during maintenance operations.
- Reproduce demands and register the consumptions as accurately as possible.
- Reproduce the real behavior of the network as accurate as possible according to the data registered by the sensors about levels, pressures and flows to be perfectly calibrated and to the model be able to reproduce all the control operations performed on the network
- The reliability of the measurements collected by the sensors, fundamental in real-time decision and in alarm detection.

As presented in Fig. 9, a virtual twin model must contain three main parts: the physical assets able to collect data that make up the smart water grid, a virtual model of the hydraulic system capable of simulating each scenario and the connection between virtual and real space responsible of feeding the hydraulic model with real information. [34]

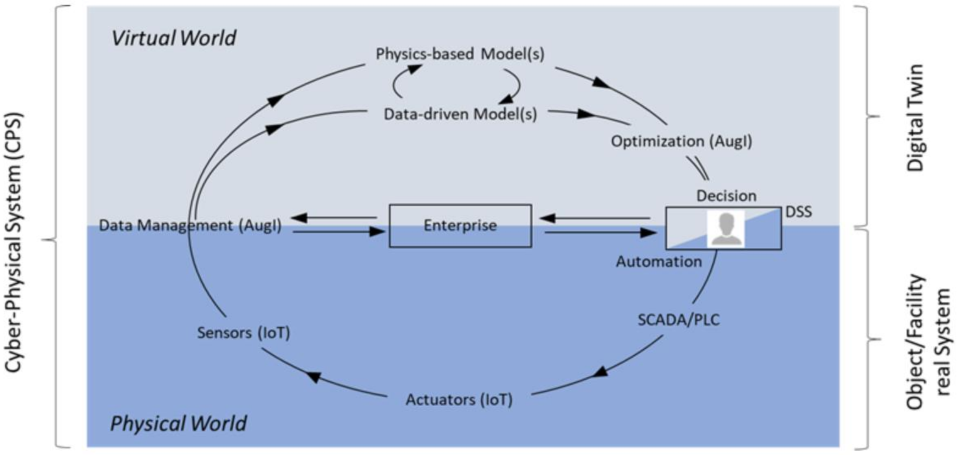

Fig. 9 - Data-streams, decision-making and implementation in a Cyber-Physical System powered by a Digital Twin [34]

Digital twin development requires continuous adjustments and learning techniques supported by large amount of field data stored in big-data platforms. The main sources to create the platform are: (i) GIS, to provide information of spatial locations; (ii) Sensors, to receive the information from the hydraulic network; (iii) Supervisory control and data acquisition (SCADA), to supervise, monitor and control the data collected; (iv) Smart Metering, to control the network operation and customer service in independent metered areas; (v) Computerized Maintenance Management System (CMMS), to track and maintain stationary assets. As a result of the integration of the mentioned sources in the hydraulic model, using artificial intelligence algorithms and Information and Communication Technologies (ICTs), a DT model is obtained (Fig. 10) and its potential can be exploited [33].

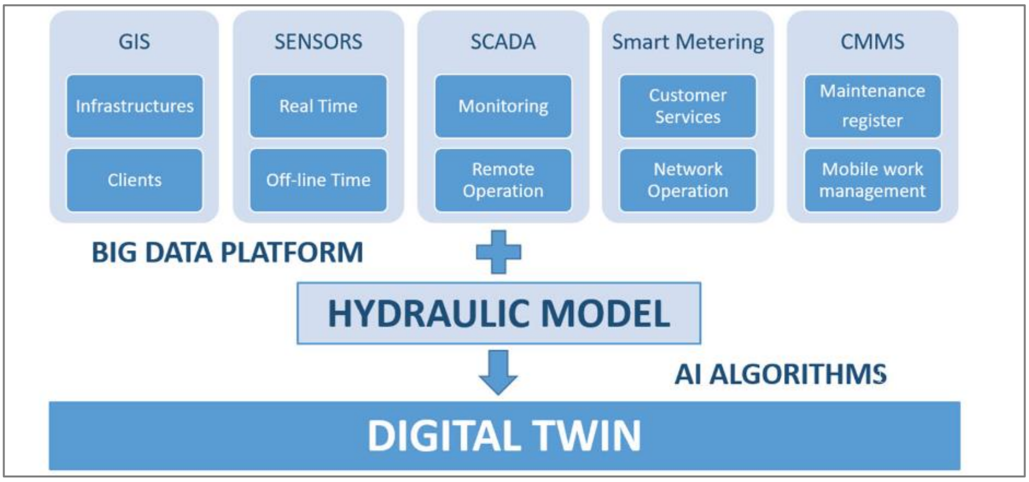

Fig. 10- WDS Digital Twin Structure [33]

3.4.2. Key Technologies for DT and types of models

Settings of offline model elements are estimated inputs, meaning that they can't represent the actual operations over a longer period horizon. With online model, these settings can be taken from real measurements, requiring a calibration process to link SCADA database to the real time model. The calibration processes allow the network to be operated in optimum conditions, since when the model is runed with the real settings, its results can be runed again in an optimization simulation, and those settings results can be applied in the real network. This process would be repeated on hourly or quarterly basis, depending on the utility's requirement. With an online model it is possible to know the costumers affected with low pressures in real time, to have constant monitoring and consequent pressure optimization [35].

Digital Twin uses different technologies to create an interface between the virtual model and the real physical object to send and receive information in real-time. To better grasp the architecture and infrastructure of Digital Twin there are key technologies that must be considered [35].

- Modelling: physical and virtual models must describe the main features of the system
- Connection: the physical and virtual system must be constantly connected. This theory includes data transmission, conversion, storing and protection.
- Data mining: data received must be processed, clean and filtered, by data analysis techniques and Artificial Intelligence (AI) in order to be applied.
- Interaction & Service: once validated the simulation, the Digital Twin must be able to suggest, optimize and adapt the system processes to external changes.

A Digital Twin is a platform formed by a set of models, depending on the sector or industry it contains different elements. In the water sector a Digital Twin should include a water process model forced to work by boundary conditions, an asset model related with GIS describing physical assets and infrastructure, used to setup and configure the water process models and performance models to generates the metrics required to make the decisions, being usually connected to the Enterprise Resource Planning (ERP) software of the organization allowing automated scheduling repairs. The different models previously referred must be linked and updated in real-time, representing all together the complete Digital Twin model [35].

Nowadays, Internet of Things (IoT) and Information and Communication Technology (ICT) have allowed the possibility to develop a Digital Twin model, but it is required a filtration of information to be properly utilized, and a big data platform to develop a Digital Twin [35].

The main data sources managed by DT are Geographical Information Systems (GIS), Automated Meter Readings (AMR), Computerized Maintenance Management Systems (CMMS), Field data stored by Supervisory Control and Data Acquisition system (SCADA) [35].

A strategy to develop and maintain a Digital Twin of a water network must be designed and integrated in the hydraulic model with all the information sources. Fig. 11 represents an example of the strategic diagram for the development of a hydraulic model. [31].

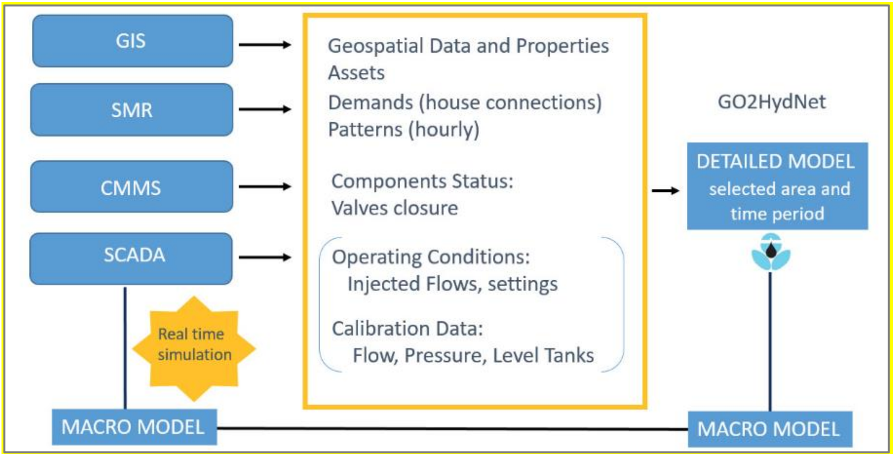

Fig. 11 - Diagram of the strategy to integrate the hydraulic model with different information source [31]

3.4.3. Digital Twin Benefits

The access to accurate and complete information in real-time through DT allows the optimization of network's performance. The continuous access to real-time water network information enables to monitor, predict, and react to disruptions or emergencies, gaining complete control over resilient infrastructure operations. Digital twin provides a 360-degree view of all the infrastructure, helping to perform diagnostics, build models, establish ideal maintenance schedules, conduct predictive and prescriptive analytics, test and evaluate scenarios, and generate actionable insights in real-time for critical and efficient decision making [36].

Digital twins enable utilities to simulate events such as pipe failure, power outages, fires, and contamination, helping utilities analyzing the resilience of their systems. Continuously updating digital twins with measured operational data helps a utility determine the location of potential leaks as well as reduce water loss. Also, integrating the hydraulic model, that most water utilities already have, with data from SCADA systems, it is obtained a digital twin that allow utilities to determine properties of their water systems that cannot be directly measured, such as water age or velocity, and simulate and test different ways that their water system could be operated to improve emergency response, increase efficiency, or save energy [31].

Using Digital Twin and data intelligence operating costs could also reduce due to:

- Decreased cost and risk of both unplanned asset downtime and scheduled but necessary maintenance
- Reduced leaks and breakage, saving wasted water
- Identification of opportunities to boost operational efficiency as they occur
- Better prediction of future demand.
- Reducing energy use and carbon emissions.

These factors help to achieve lower financial costs and generate new income translating into larger working funds (cash flow).

Finally, longer-term benefits include: improved planning and preparedness, enhanced infrastructure resilience and sustainability, ensured continuity of service without incident, and prediction of future renewal needs. Achieve permanent reduction in production, maintenance, emergency and operational costs [37].

As previously mentioned, a Digital Twin infrastructure can do more than water network simulations, being able to predict and optimize system's behavior, monitoring asset health and performance, and timely recognize potential anomalies. The simulation of the operation of assets, their surrounding environment and the interact in real-time enable users to test possible futures scenarios, view and compare outcomes in other to optimize asset performance, resulting in informed decisions and the consequent improvement of the system efficiency by the reduction of water losses, pressure control, leak detection, system repairs, among others. Fig. 12 represents the optimization process due to a Digital Twin Model proposed by Paul Boulos [37].

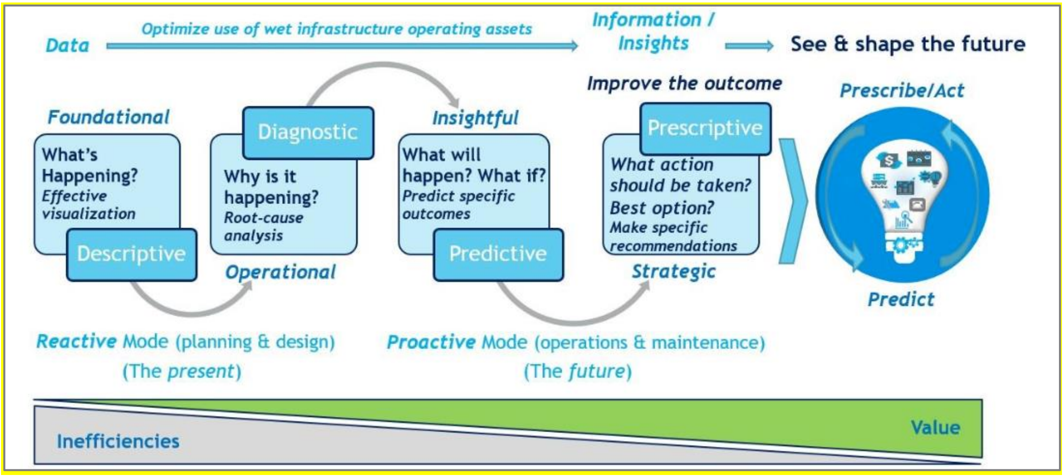

Fig. 12- Proactive DT model proposed by Paul Boulos [37]

4. CASE STUDY – SANTA CRUZ WATER DISTRIBUTION

4.1 Overview

Being essential for all forms of life, water is an irreplaceable natural resource, increasingly scarce, whose waste must be avoided. In the case of water supply and distribution systems, this waste is essentially reflected in water losses that occur, due to degraded network components, poor management of pressures by the managing entity, ruptures that occur in the system, illicit thefts, measurement errors, among others. Therefore, a study of a Water Distribution System located in the Portuguese island Madeira, managed by Municipality of Santa Cruz (MSC), will be performed. This system's current situation is extremely warning, since only about 30% of the incoming water is effectively billed to consumers, meaning that the remaining 70% represent water losses.

All data used in this study was provided by the Municipality of Santa Cruz and RSS – Redes e Sistemas de Saneamento, lda, through their projects about Reduction of Water Losses in the Water Distribution System of the Municipality of Santa Cruz, in which the existing water distribution network was reformulated and analyzed.

With energy dependence being an increasingly relevant concern nowadays, the data mentioned and analyzed will also be the starting point of a feasibility study for the implementation of green energy production solutions, considering the implementation of turbines in the WDS, taking advantage of pup as turbines (PAT) recovering energy.

4.2 Methodology

The first step that must be assured to develop a hydraulic model of an existing network is the data collection (Fig. 13), mainly provided by the municipality or other management entities, to represent accurately the existing network.

Firstly, terrain modeling data must be provided, alongside with network physical data (Pipe's, junction's, valves or other existing devices, reservoirs and connection's). Also, cartography and buildings characteristics (top elevation, number of floors, eventual pump existence) are required for pressure and water supply management understanding.

Besides physical data it is also required system's volumes and all measured information, to identify flow patterns, costumers' consumptions, and the overall volume balance of the system according to Water Balance definition. Finally, field pressure measurements are the key to understand if the digital model is describing accurately what's happening in the real system.

After data collected, methodology shortly presented in Fig.13 should be followed in order to develop a digital twin of a real water network in Epanet Sotware.

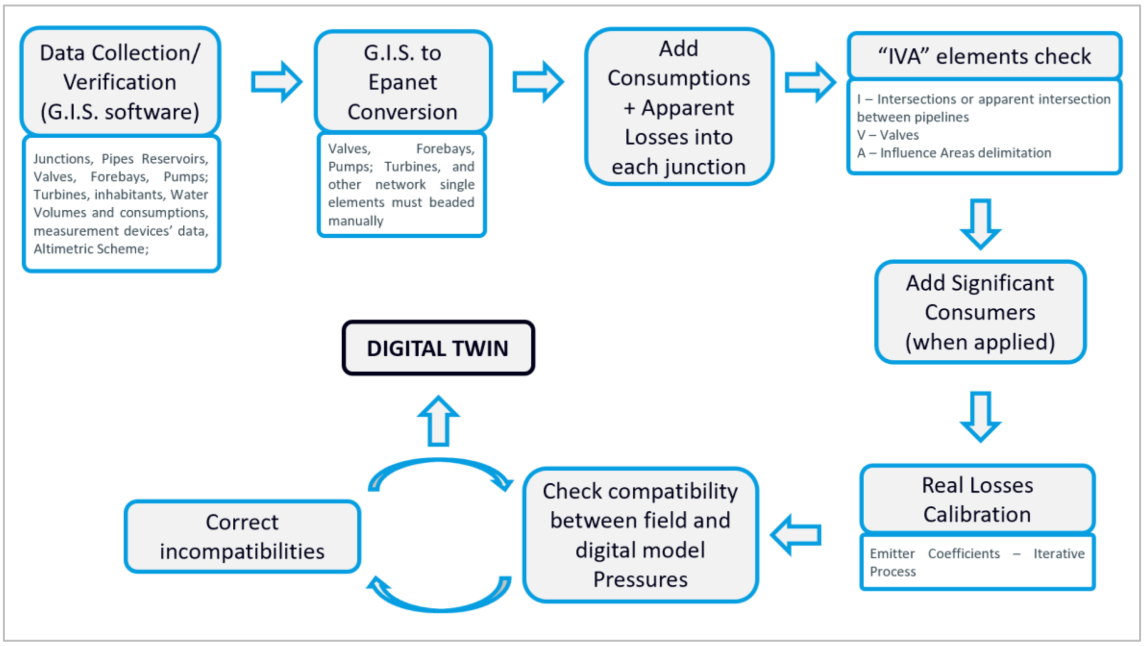

Fig. 13 – Methodology to Develop a Digital Twin

4.3 Santa Cruz WDS characteristics

According to *PORDATA*, Santa Cruz is the second municipality with more inhabitants in Madeira Island. Located in the Atlantic Ocean, this island is characterized by its very variable altimetry, and the consequent high slopes of the water distribution network's pipelines. Fig. 14 presents Santa Cruz morphology considering the altimetry provided by the MSC, where it is verified that in an area of 81 km^2 there are altitude values varying between 0 and more than 1000 meters.

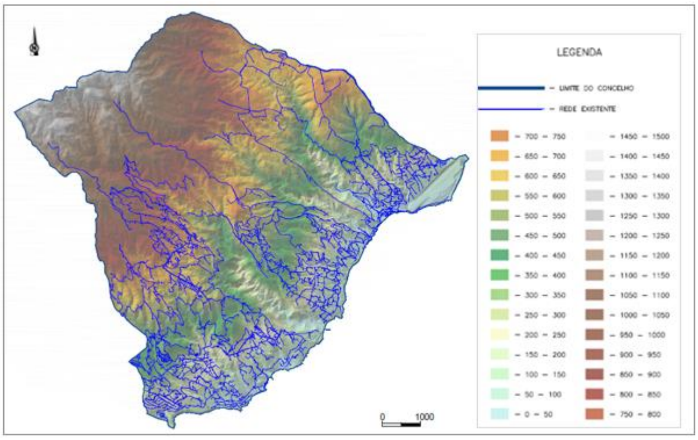

Fig. 14 – Morphology of Santa Cruz (Madeira)

As for the water supply system, it develops from a set of pipelines, reservoirs and springs. The municipality has residential and touristic occupation being supplied by 42 reservoirs, represented in Fig. 15, Table 3 and Table 4, mainly gravitic.

The water distribution systems is aged, with 437 km of pipes, distributed in 41 Influence Areas (IA) as presented in Fig. 16. The network's material is mainly HDPE (46%) and PVC (27%), and 91% of pipe's diameter is lower than DN140.

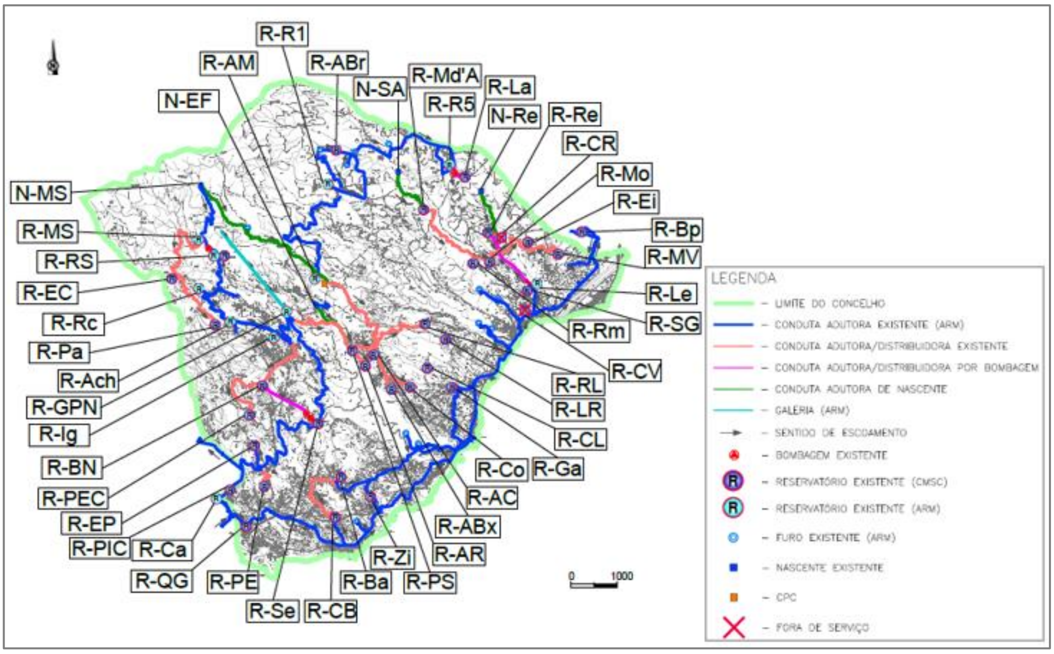

Fig. 15 – Water Supply System (WSS) of Santa Cruz

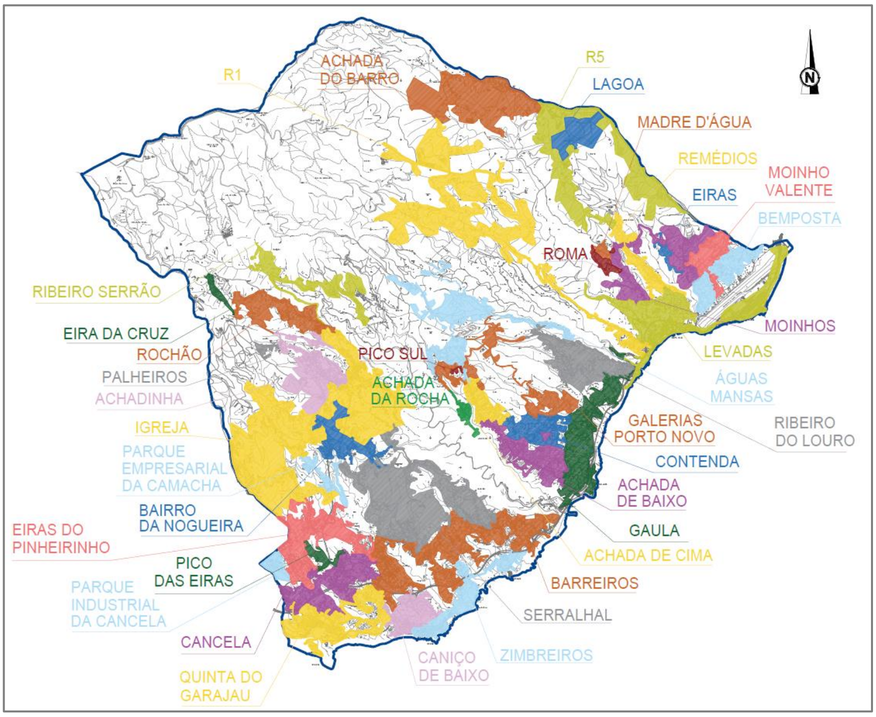

Fig. 16 – Influence Areas of Santa Cruz WDS

Table 3 – Spring of Santa Cruz Water Supply System

ID	Name	Elevation
N-EF	Nascente Eiras de Fora	658
N-MS	Nascente Meia Serra	1140
N-Re	Nascente Remédios	500
N-SA	Nascente Serrado das Ameixeiras	605

Table 4 – Reservoirs of Santa Cruz Water Distribution System

ID	Name	Elevation	Volume (m3)	Management Entity
R-ABr	Achada do Barro	736	184	CMSC
R-ABx	Achada de Baixo	453	100	CMSC
R-AC	Achada de Cima	526	32	CMSC
R-Ach	Achadinha	877	500	ARM
R-AM	Águas Mansas	771	1000	ARM
R-AR	Achada da Rocha	511	24	CMSC
R-Ba	Barreiros	285	1000	CMSC
R-BN	Bairro da Nogueira	695	1000	CMSC
R-Bp	Bemposta	229	4000	CMSC
R-Ca	Cancela	410	4000	ARM
R-CB	Caniço de Baixo	164	1000	CMSC
R-CL	Caminho do Lombo	329	10	CMSC
R-Co	Contenda	419	100	CMSC
R-CR	Capela dos Remédios	424	-	Disabled
R-CV	Centro da Vila	54	-	Disabled
R-EC	Eira da Cruz	1067	20	CMSC
R-Ei	Eiras	329	100	CMSC
R-EP	Eiras do Pinheirinho	565	1000	CMSC
R-Ga	Gaula	179	2000	CMSC
R-GPN	Galerias de Porto Novo	623	2000	ARM
R-Ig	Igreja	775	2000	ARM
R-La	Lagoa	743	30	CMSC
R-Le	Levadas	188	500	ARM
R-LR	Levada Roda	320	28	CMSC
R-Md'A	Made d'Água	513	100	CMSC
R-Mo	Moinhos	368	100	CMSC
R-MS	Reservatório Meia Serra	1111	10	ARM
R-MV	Moinho Valente	275	100	CMSC
R-Pa	Palheiros	935	22	CMSC
R-PE	Pico das Eiras	482	1000	CMSC
R-PEC	Parque Empresarial da Camacha	676	250	CMSC
R-PIC	Parque Industrial da Cancela	449	1000	CMSC
R-PS	Pico Sul	567	32	CMSC
R-QG	Quinta do Garajau	314	1000	CMSC
R-R1	R1	846	1200	ARM
R-R5	R5	723	1000	ARM
R-Rc	Rochão	989	500	ARM
R-Re	Remédios	425	1000	CMSC
R-RL	Ribeiro do Louro	406	200	CMSC
R-Rm	Roma	402	100	CMSC
R-RS	Ribeiro Serrão	937	1000	CMSC e ARM
R-Se	Serralhal	569	500	CMSC
R-SG	São Gil	188	500	CMSC
R-Zi	Zimbreiros	164	1000	CMSC

According to Água e Resíduos da Madeira (ARM - Water and Wastewater Madeira Management Entity), that provided WSS's values, and MSC, that provided WDS's values data, Table 5 indicates the annual volumes acquired by the municipality and the correspondent annual billed/unbilled volumes.

Table 5– Annual Volumes – Santa Cruz (ARM and MSC data)

Year	Acquired Annual Volume	Billed Annual Volume	Unbilled Annual Volume	Unbilled/Acquired
(-)	(m3)	(m3)	(m3)	(%)
2010	7.211.432	2.810.567	4.400.865	61,0
2011	7.434.454	2.705.859	4.728.595	63,6
2012	7.688.409	2.656.678	5.031.731	65,4
2013	8.094.031	2.370.288	5.723.743	70,7
2014	8.011.062	2.406.423	5.604.639	70,0
2015	8.654.570	2.429.246	6.225.325	71,9
2016	8.774.399	2.481.348	6.293.051	71,7
2017	9.065.322	2.540.274	6.525.048	72,0
2018	9.233.381	2.444.474	6.788.907	73,5
2019	9.574.240	2.511.736	7.062.504	73,8

A brief analysis shows that more than 7M m^3/year is not billed, representing 74% of the total acquired volume. Also, Billed Volume has remained stable over the years, which indicates that the apparent losses should not be varying substantially, which must be essentially due to errors in measure devices. The evolution of "Unbilled Volume" shows that the total losses are increasing dangerously. Unbilled Authorized Consumption (UAC) component, corresponding to MSC expenses and water intentionally not billed, may correspond to a significant portion of the "Unbilled Volume". In conclusion, the portion that has the most weight in the increase of the Volume of Unbilled Water, which in 2019 corresponds to 73.8% of the Volume Entered, is Real Losses.

The unbilled values observed in Table 5, despite being higher than the national average, would be expected considering the existing topography, excessive pressures observed and a considerable degradation of the water distribution network.

A digital twin of Santa Cruz System was elaborated in order to study these variables in more detail. In the following chapter the used methodology will be presented through the example-model of Gaula, the WDS supplied by Gaula's Reservoir. The explained methodology was followed for all the other systems.

4.4 Digital Twin of Gaula WDS

4.4.1. Starting Conditions

A Digital Twin was developed individually to each subsystem of Santa Cruz WDS, with *EPANET* software, and after being calibrated it was compiled in a single model. To explain the methodology adopted in all other subsystems, the water distribution network supplied by the Gaula's tank was considered as a reference system. All the location and characteristics of physical elements used in the elaboration of the hydraulic model, like pipes' location and geometry, valves and tanks, as well as information related to the existing altimetry and cartography, were provided by MSC in GIS format.

The reference-system, Gaula's WDS, located in the southeast area of the municipality, contains about 19km of pipe extension.

a) Geometry

Gaula tank, located in the southeast area of the Municipality, is gravitationally supplied by "*Funchal – Machico*" pipeline. In Fig. 17 it's represented the morphology, where it can be observed the highest elevation values in the Northwest region, decreasing "in parallel" to the coast.

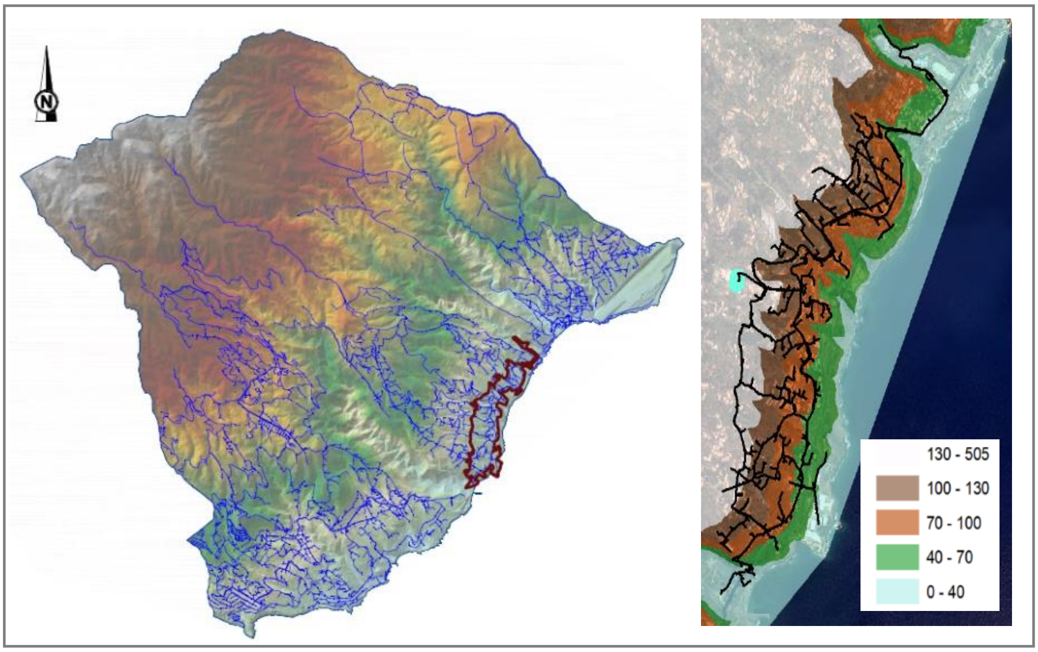

Fig. 17 - Gaula – Location and Morphology

Gaula's WDS, according to MSC data, is an aged system mostly composed by HDPE (53%) and Galvanized Iron (35%). For hydraulic simulation purposes, Hazen-Williams formula was adopted to calculate headlosses with a roughness coefficient "C" of 140 for new pipes in HDPE or FF, 130 for existing FF and HDPE, 120 for PVC or Steel and 100 for in Fiber Cement or Galvanized Iron ducts.

Fig. 18 represent the existing diameters in WDS and Fig. 19 presents diameter distribution through the network, being 56% with diameter values lower than the minimum regulated (DN60, for populations below 20 000 inhabitants). In Fig. 18 it can also be observed that 56% of the connections have diameter values lower than minimum regulated (DN 20), and that 96% has a diameter below DN40. For modeling purposes, the internal diameters were used according to the material of each pipe.

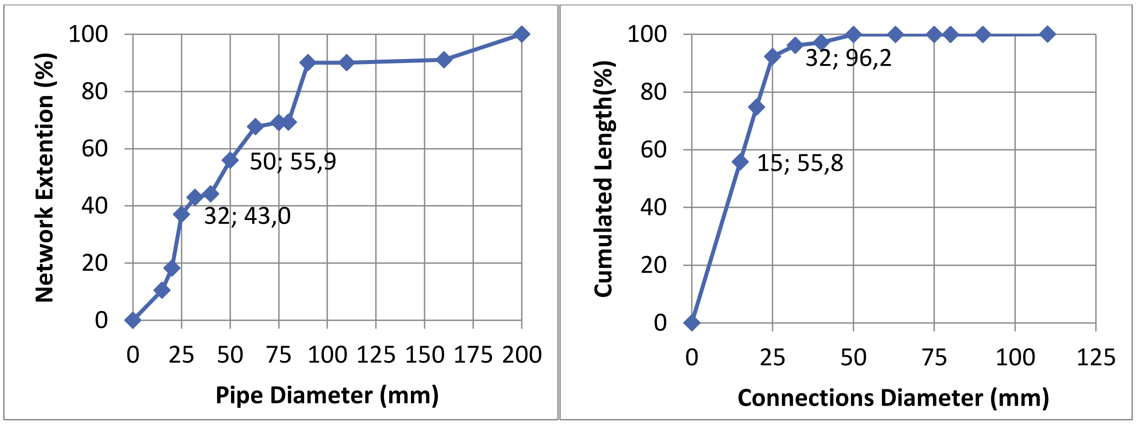

Fig. 18– Pipelines by Diameter (Left-WDS, Right - Connections)

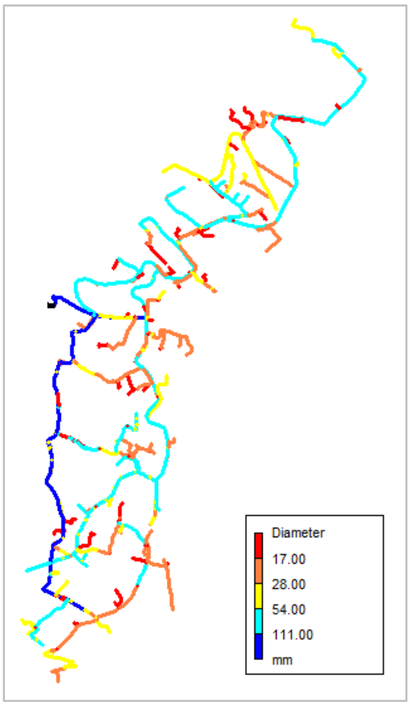

Fig. 19– Diameter Distribution

b) Domestic Consumptions and Apparent Losses

According to the information provided by the MSC, over the last few years consumption evolution has not significant variation, keeping stable values over the last few years. Therefore, it has been used, in the elaboration of the hydraulic model of the entire municipality of Santa Cruz, the values of the year 2018 for being the last year with known values at the time of the model's development. Although apparent losses typically account for about 5 to 10% of the consumption billed, it was admitted that, in the present case, they would represent twice as much, as actual losses still have a very high value. Thus, the base scenario considered is what is presented in Table 6.

Table 6 – Gaula – Volumes (2018)

Volume		
Type	(m3)	(%)
Input Volume	548 286	100
Billed	95 011	17,3
Unbilled	453 275	82,7
Apparent Losses	19 002	4,2
Real Losses	434 273	95,8

According to Portuguese National Statistical Institute data (INE website), the population being studied corresponds to 1396 inhabitants.

Since different types of solicitations occur in a distribution network, three scenarios were considered: average situation (occurrence of average consumption), peak situation (occurrence of consumption in a high-demanded situation, calculated through the application of Reglementary Instantaneous Multiplying Factor) and the static situation considering an hypothetic limit scenario in which there are no domestic flow rates or water losses, meaning the system has to carry the highest possible values of pressure.

The consumption flow rates and Apparent Losses were distributed by the junctions of the hydraulic model together, being the last one mostly resulting from measurement errors in the measurement devices. These values were introduced considering the population's distribution per node of the model, being later converted to demands applying a multiplying factor.

To calculate population of each node, Thiessen polygons were created from the junctions of the model, overlapped to BGRI Polygons, reaching a population value to be attributed to each node. The multiplier to be applied to all junctions was then determined to convert inhabitants into consumption, both for the medium and the peak scenario. This multiplier was calculated by dividing the average consumption flow of each scenario by the population to be supplied, as indicated in the Table 7.

In equation [4] is presented the Reglementary Instantaneous Multiplying Factor (*f*) calculation, where *P* represents the number of system's inhabitants.

$$f = 2 + \frac{70}{\sqrt{P}} \quad [4]$$

Applying the equation to the present case study, *f* value corresponds to 3,874, being applied only to "domestic" consumption. Fig. 20 represents the final multipliers, applied in the hydraulic model, in order to simulate the average and peak scenarios.

Table 7 – Hydraulic Model – Multipliers

Item	Value
Billed Volume (m3)	95 011
Apparent Losses Volume (m3)	19 002
Inhabitantes	1396
Reglementary Instantaneous Multiplying Factor (f)	3,874
Average Flow (excluding Real Losses) (l/s)	3,6
Peak Flow (excluding Real Losses) (l/s)	14,0
Multiplier – Average Consumption Scenario	0,00259
Multiplier – Peak Consumption Scenario	0,01003

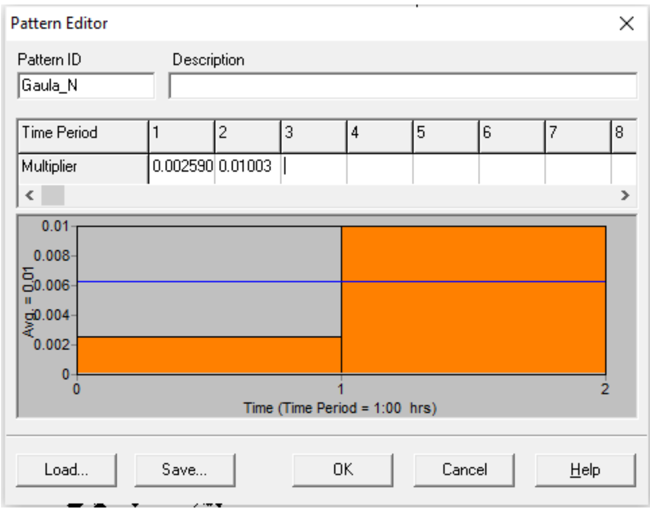

Fig. 20 – Average and Peak Multipliers – Epanet

c) Consumers with significant Consumptions

Of all customers in the municipality of Santa Cruz, there are several considered to have significant consumptions, being included in this group those whose annual consumption of the year 2018 was higher than 2,000 m^3.

In Fig. 21 it's represented the location of the 39 consumers under the conditions described none of which located in Gaula area.

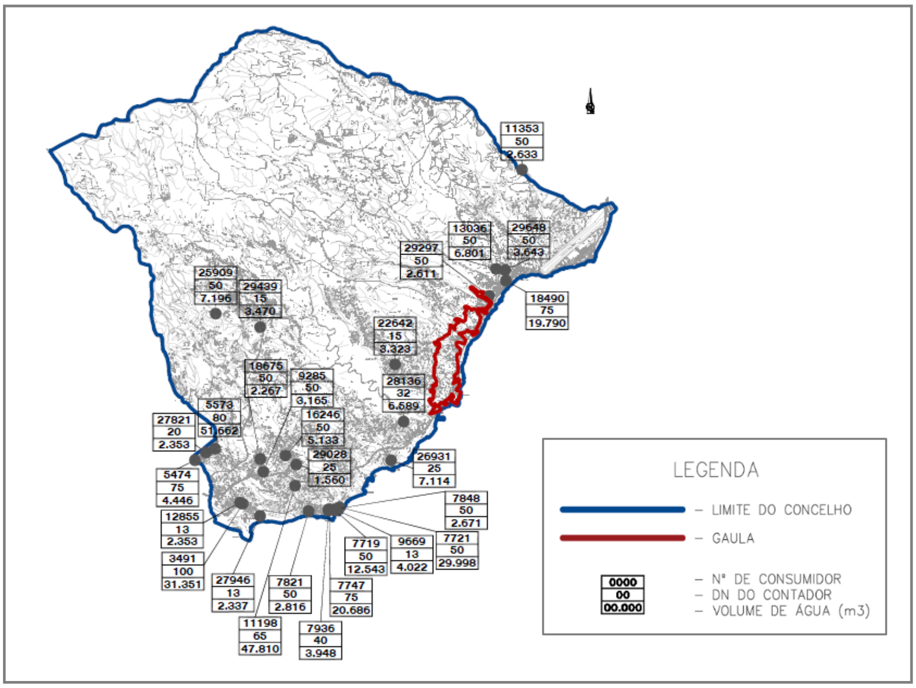

Fig. 21 – Consumers with significant Consumptions - Santa Cruz Municipality

Since the hydraulic model was elaborated independently for each one of the subsystems, the referred consumers had to be considered in the belonging systems, through an adjustment of the consumption parameters mentioned above.

In the first place, it was necessary to convert the consumption of each consumer into "equivalent inhabitants", according to the fallowing methodology:

> -A "new" value of daily consumption per inhabitant was calculated for the system, dividing a new annual consumption (corresponding to tank output volume excluding annual consumption of the Significant Consumers of the system in analysis) by the number of inhabitants [m^3/inhab/year].
>
> -The number of equivalent inhabitants was determined by dividing the Significant Consumer's annual consumption value by the "new" daily consumption per inhabitant.

Once the number of equivalent inhabitants was determined, it was necessary to recalculate the multiplier values so that the hydraulic model represented the total consumption effectively verified in each zone, since the hydraulic model will have a higher number of inhabitants than the existing value.

In systems with significant consumers, the Reglementary Instantaneous Multiplying Factor (*f*) was considered equal to 3 to those consumers and, fallowing the same methodology used in remaining systems, to the regular consumers it was applied a value calculated by equation [4], where the "new" value of inhabitants was applied.

Two consumption patterns were stablished for each subsystem, one for junctions corresponding to Significant Consumers, and a second one to current consumers, being the average situation multiplier a constant value for all junctions in the system and calculated according to the methodology presented above.

d) Real Losses

As shown in Table 6, Real Losses represent 95% of the system's total water losses. In the hydraulic model, Real Losses volume were considered separately from apparent losses and demands, through the introduction of emmiter coefficients. With this approach, the digital twin have different variables associated to each node, being the real losses simulated with a discharge of a flow rate, independent from consumption. The flow discharged from each node is calculated according to the expressions [5] and [6], in which q represents *the* flow rate, K_f *the* discharge coefficient, p the pressure, g the pressure exponent that depends on the type of material of the network, c the discharge coefficient, L_{ij} the length of the pipe between the junctions i and j and M is the number of conduits connected to node j [38].

$$q_j = K_f \, p_j^{\gamma} \qquad [5]$$

$$K_f = c \times \sum_{J=1}^{M} 0.5 \times L_{ij} \qquad [6]$$

The first step of this process was the conversion of the annual consumption and losses volumes into average flow rates (l/s). Considering equations [5] and [6], the flow rates corresponding to Real Losses were distributed into each node, through an iterative process, until MSC provided values were reached.

The iterative process began with an initial value of $1\text{x}10^{-5}$ assigned to the discharge coefficient, and then applied, to each node, with the sum of half of the length of each converging pipe. This variables product resulted in a first group of values to be applied to the emitters coefficients of the hydraulic model, and those values generated an output flow from the reservoir.

Since domestic consumption and Apparent Losses were considered a constant values and already determined, it was possible to calculate the Real Losses correspondent flow and through that value readjust the emitters coefficients until the result reached MSC values.

The iterative process was considered as finished when the difference between MSC Real Losses flow and the hydraulic model RL reached 0.01 l/s.

Table 8 indicates the summary iteration values, being the complete process and the evolution of each node presented in Appendix I.

Table 8 – Hydraulic Model – Real Losses (Emmiters) – Iterative Process

Iteration	1		2		3	
MSC Values	(m3/year)	(l/s)	(m3/year)	(l/s)	(m3/year)	(l/s)
Tank Volume	548 286.00	17.39	548 286.00	17.39	548 286.00	17.39
Consumption + Ap.Losses	95 011.00	3.01	95 011.00	3.01	95 011.00	3.01
Real Losses	434 272.80	13.77	434 272.80	13.77	434 272.80	13.77
Simulation Values	(m3/year)	(l/s)	(m3/year)	(l/s)	(m3/year)	(l/s)
Tank Volume	682 439.04	21.64	557 241.12	17.67	534 219.84	16.94
Consumption + Ap.Losses	95 011.00	3.01	95 011.00	3.01	95 011.00	3.01
Real Losses	587 428.04	18.63	462 230.12	14.66	439 208.84	13.93
Ci= RL(CMSC)/RL(Simul)	0.73928		0.93952		0.98876	

Iteration	4		5	
MSC Values	(m3/year)	(l/s)	(m3/year)	(l/s)
Tank Volume	548 286.00	17.39	548 286.00	17.39
Consumption + Ap.Losses	95 011.00	3.01	95 011.00	3.01
Real Losses	434 272.80	13.77	434 272.80	13.77
Simulation Values	(m3/year)	(l/s)	(m3/year)	(l/s)
Tank Volume	530 120.16	16.81	529 489.44	16.79
Consumption + Ap.Losses	95 011.00	3.01	95 011.00	3.01
Real Losses	435 109.16	13.80	434 478.44	13.78
Ci= RL(CMSC)/RL(Simul)	0.99808		0.99953	

e) Pressure Reduction Valves

Gaula Water Distribution System has 10 Pressure Reduction Valves (PRV) and one forebay. Most of the existing PRV were regulated to pressure values much higher than the "ideal regulation" (in the order of 2 bar), as illustrated in Table 9 and Fig. 22.

Table 9 – Existing PRV Regulation

PRV	Designation	Existing Regulation (bar)	"Ideal" Regulation (bar)	Difference (bar)	Existing/ "Ideal" (%)
Lajes Norte	LC	1,9	2,0	-0,1	95,0
São Pedro	SP	2,8	2,0	0,8	140,0
Rosário + Fazendinha I	R+FI	3,0	2,0	1,0	150,0
Fazendinha II	FII	3,5	2,0	1,5	175,0
Gato Norte	GA	3,7	2,0	1,7	185,0
Gato Sul	GB	3,7	2,0	1,7	185,0
Lajes Sul	LB	3,9	2,0	1,9	195,0
Lombadinha I	LI	4,9	2,0	2,9	245,0
Lombadinha II	LII	5,6	2,0	3,6	280,0
Lombadinha III	LIII	6,6	2,0	4,6	330,0

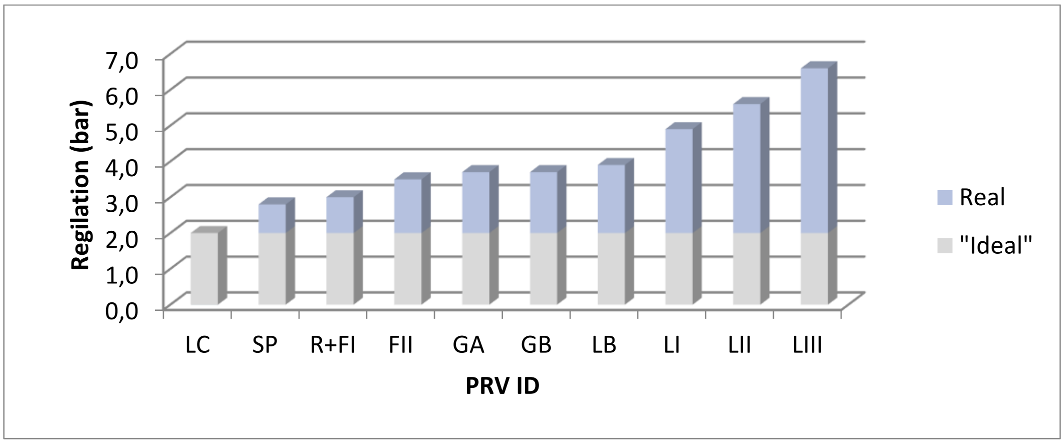

Fig. 22 – Existing PRV Regulation

In the initial system's conditions only 1 in 10 VRP would have an "ideal" regulation. This may have happened, among other possibilities, because some areas may have low pressures and a consequent deficient supply, due to insufficient diameters, being necessary to stablish high pressure regulations in order to solve this problem, creating an additional excess pressure in the rest of the network.

f) Hydraulic Model Calibration

In order to understand the veracity of the hydraulic model, pressure results were compared with real measurements performed in 54 points of the distribution network, as shown in Fig. 23, where it can be observed that, there is an almost perfect correspondence between the measured and the calculated values, with an average 5% error into the peak hour. Since most values were measured around 9 a.m., the hydraulic model corresponds to peak situation. However, some measurements were made in the middle of the morning or in the afternoon, being closer to those average situation results.

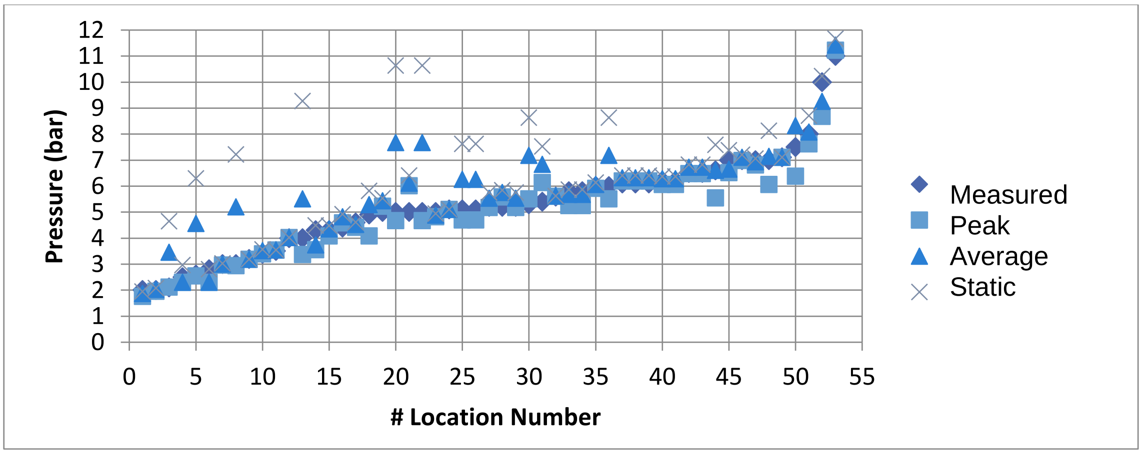

Fig. 23 – Measured and Simulated pressure values

4.4.2. RSS Changes Proposal

The presented hydraulic model describes RSS changes proposal to improve the functioning of the water distribution system, and it will be the starting point scenario to analyze renewable energy possibilities.

In Gaula WDS, due to the existing low diameter values, high values flow speed and unit headlosses values are verified, both in the medium and peak situations, being this the most relevant criteria for the replacement of pipelines, to improve overall hydraulic functioning of the system.

Fig. 24 presents unit headlosses in the peak scenario of existing situation and proposed situation. It's also presented the replaced pipes, being shown the direct influence of low diameters values in WDS. Pipelines with higher unit headloss values were, in most cases, replaced or complemented with another one, controlling the original flows responsible for those values of headlosses.

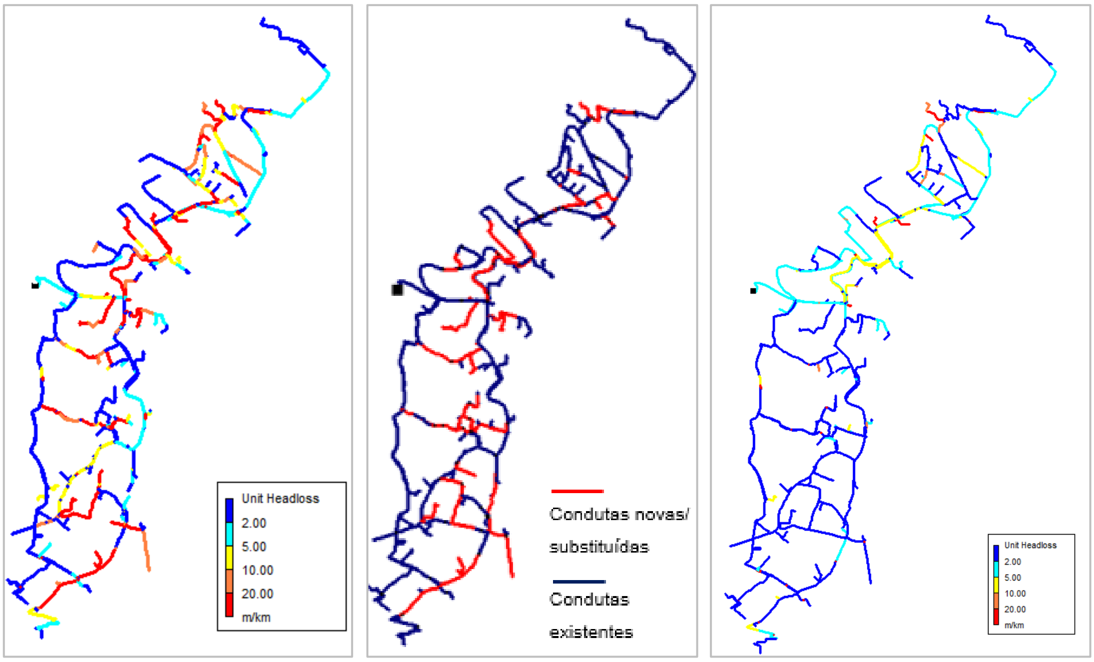

Fig. 24 – Unit Headlosses – Peak Scenario (Existing situation); New/Replaced Pipelines; Unit Headlosses – Peak Scenario RSS Proposal

In parallel with pipeline replacement, the network was also divided into smaller areas to easily control anomalous consumption patterns and water theft or breakage. Therefore, 6 District Metered Areas (DMA) were created, according to the characteristics presented in Table 10 and Fig. 25 where flow meters are indicated as C or V if they are associated with Pressure Reduction Valves.

Table 10 – DMA – Characterization

System	DMA	Flow Controlers	Extention (km)
Gaula	1	C1-V21-V20-C2-V18	4,2
	2	C2-V12	4,6
	3	V20+V21-V22	5,8
	4	V12	3,6
	5	C3+V18	3,5
	6	V22-C3	5,3
	Total	C1	27,0

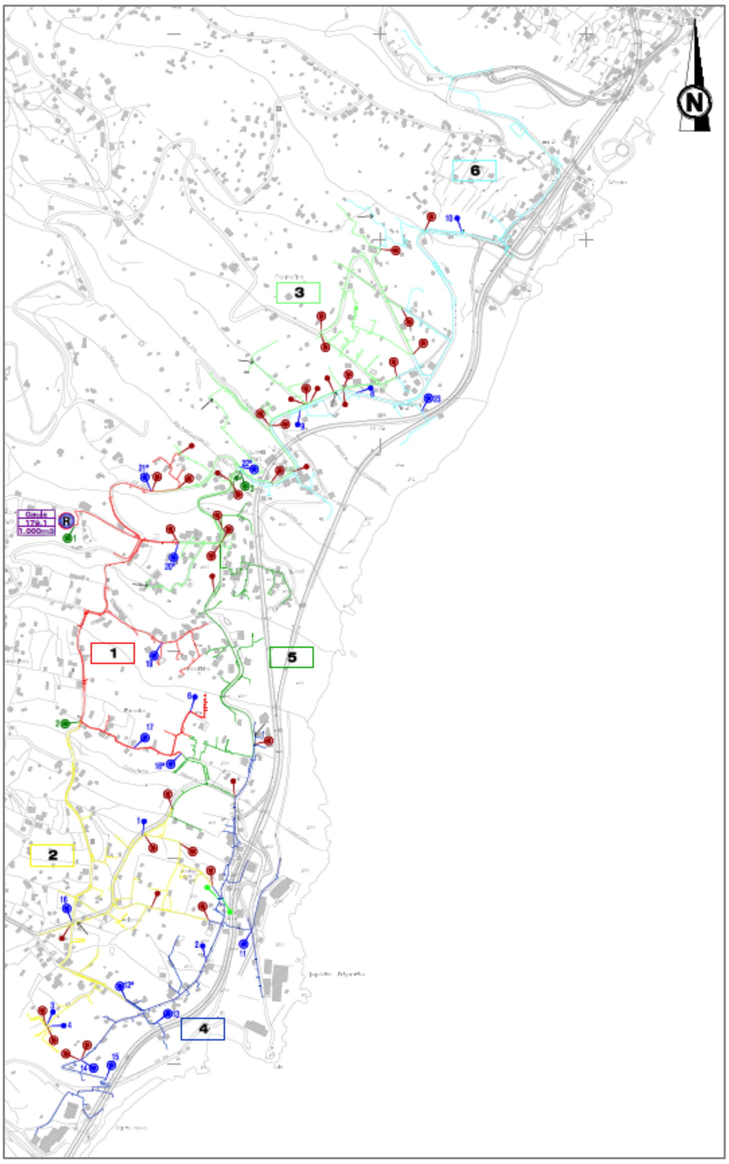

Fig. 25 – DMA - Gaula

4.4.3. Analysis of Network Pressures

After the development and calibration of the Hydraulic models, a brief analysis was made to understand pressure values improvement. Therefore, Fig. 26 and Fig. 27 present pressure values occurring in systems in the existing scenario and after RSS proposed changes.

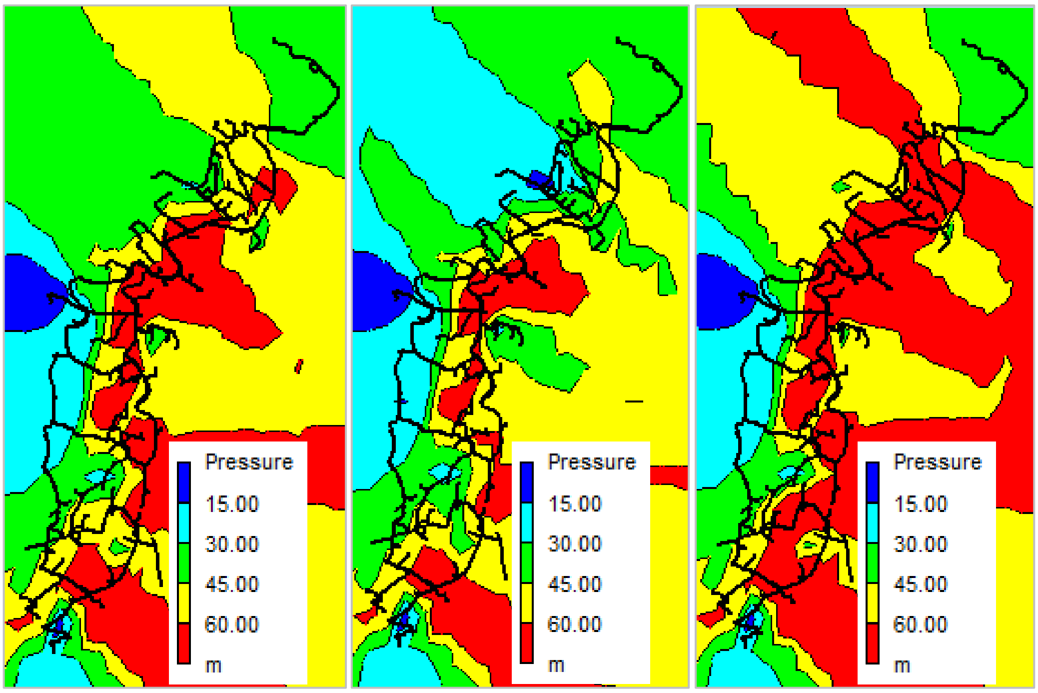

Fig. 26 – Gaula – Average, Peak and Maximum pressure scenarios (Existing Situation)

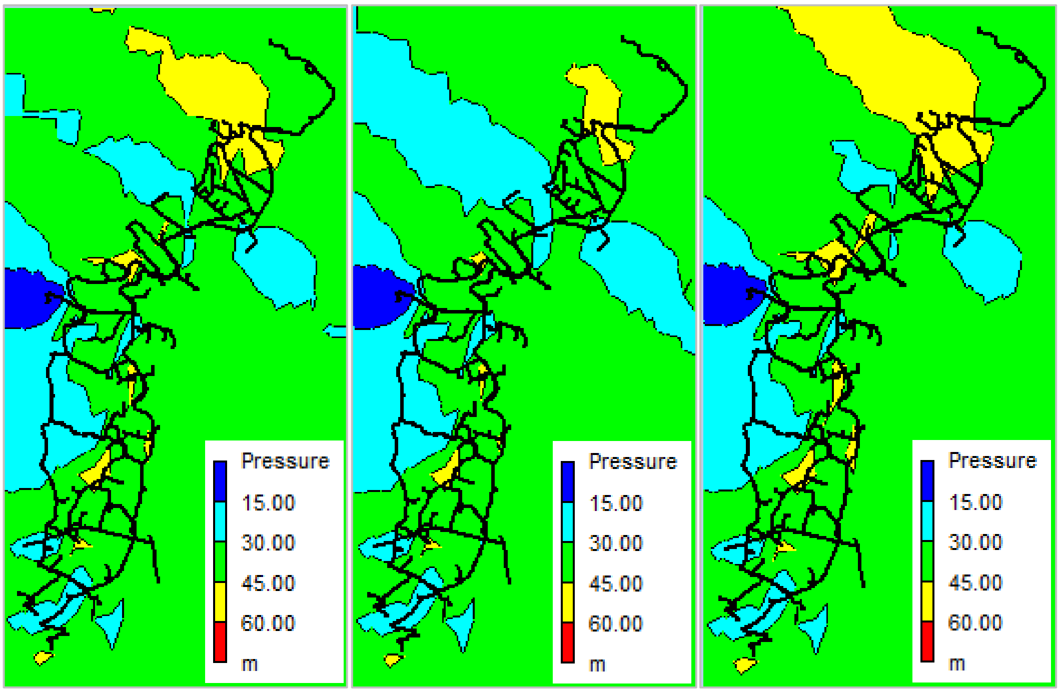

Fig. 27 - Gaula – Average, Peak and Maximum pressure scenarios (RSS Proposed Situation)

Table 11 and Fig. 28 present pressure values in the network junctions, obtained from the hydraulic models, allowing some conclusions to be taken about the verified pressures reduction.

Table 11 – Pressure in Junctions – Epanet Results

		% of junctions with pressure values below:									
		10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Pressure (mc.a.)	Existing-Average	23.00	25.72	31.87	38.78	50.77	56.27	63.4	68.77	75.68	114.2
	Existing - Peak	19.69	35.18	42.43	49.54	45.43	51.42	56.31	63.07	71.25	112.47
	Existing - Static	23.74	20.08	30.06	40.03	56.17	62.46	69.93	79.1	86.21	122.26
	Future - Average	20.39	23.69	27.20	30.50	33.58	37.9	41.7	45.68	54.07	69.24
	Future - Peak	19.71	22.80	26.26	30.00	32.72	37.04	41.08	44.6	52.9	67.56
	Future - Static	20.77	24.50	27.89	30.74	34.19	39.1	42.07	47	55.35	70.03

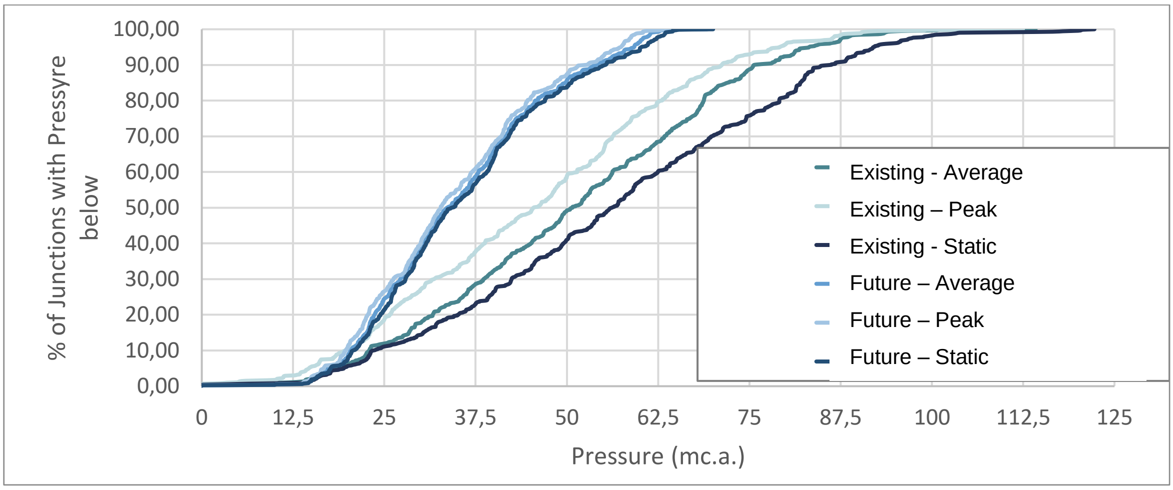

Fig. 28 – Pressure in Junctions – Epanet Results

Comparing the average pressure observed in the average scenario of the existing and changed models, there is a reduction of 1.7 bar compared to the 5.1 bar verified in the existing situation model, where about 25% of network's junctions have pressures values above 60 mc.a. (maximum regulatory) in all scenarios analyzed (medium, peak and static).

By simulating the extreme situation (static), where consumption and losses were considered non-existent, the reduction of the mean pressure value obtained was from 56 mc.a. to 34 mc.a., being a reduction around 2 bar.

As for the junctions of the proposed network with pressures above the regulatory maximum of 60 mc.a., in the average situation less than 4% are in this situation, and in the maximum limit situation only 6% reach those pressure values, meaning that with sectorization and requalification of the network, the excess pressure problems will be substantially mitigated.

Applying proposed changes by RSS in the existing WDS, there will not only be a reduction in pressure values but also its variability will become smaller. It should also be noted that in the proposed network, pressure values have no significant variation with the time, as is noted in the current situation.

Fig. 29 shows the relationship between the ruptures that occurred in the Gaula's network and the pressures observed in the place where they occurred, according to the information provided by the MSC, from which it can be observed the strong dependence between the two variables. As excessive pressures are one of the biggest problems in systems with high volumes of water losses, this was one of the aspects to be considered when reshaping the network.

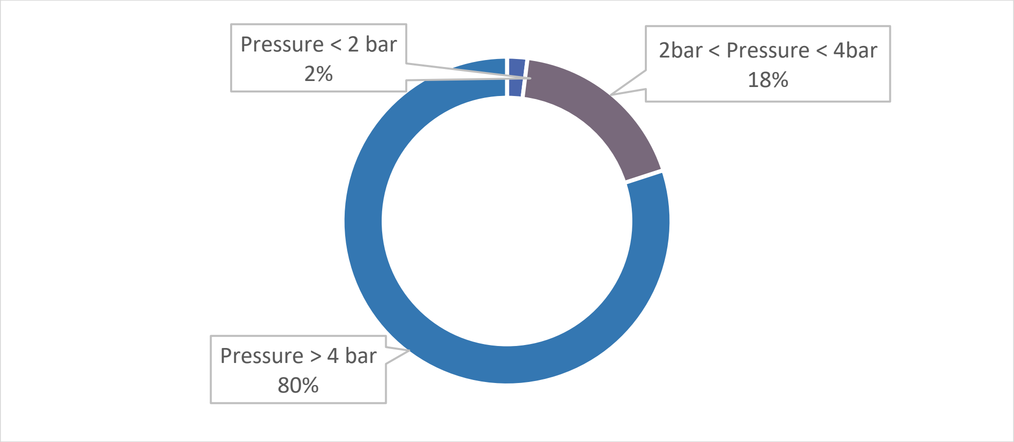

Fig. 29 – Percentage of Ruptures (Static Scenario)

4.4.4. Water Losses Analysis

Among the various losses' components, Real Losses have greatest weight, which in this case is about 95% of the total losses' volume. Thus, in the analysis of the results presented below, it was considered that the consumption and Apparent Losses remained constant, being variable only the volume of Real Losses.

Table 12 shows a comparison between the volumes verified in the year considered as the existing situation (2018), the year when the proposed changes were finished and the hypothetical target to be achieved according to PEAASAR (Portuguese Supply and Residual Water Strategic Plan) in Gaula WDS.

Table 12– Annual Volumes - Gaula

Situation	**Total Volume (m^3)**	**Billed Volume (m^3)**	**Unbilled Volume (m^3)**	**UV/TV (%)**
Existing situation (2018)	548 286	114 013	434 273	79.2%
Target (PEAASAR II)	196 255	114 013	82 242	15.0%
Difference	-352 031	0	-352 031	-
Proposed Scenario	344 373	114 013	230 360	66.9%
Difference	-203 913	0	-203 913	-

By implementing the proposed scenario simulated in the hydraulic model, it would be necessary only 40% of the annual volume entering the system in 2018 to supply Gaula's network. However, due to the very high value of losses that occur in the system, this reduction would not be enough to achieve the objective proposed in PEAASAR where a target of 15% of water losses should be reached. In a scenario where the proposed PEASSAR goal would be achieved, it would be necessary to acquire only 1/3 of the water volume entering in the existing situation.

An indicator that allows not only knowing existing Real Losses but also a good approximation to their reduction potential is the Infrastructural Leakage Index (ILI) which consists of the ratio between the value of Actual Real losses and the "minimum" value of Real losses (UARL), as mentioned in chapter 2.2.

In the existing scenario, being the average pressure of 5.1 bar verified in the digital twin model and considering an average extension between properties and the connection to the common conduit of 10 meters, results in the UARL values illustrated in Fig. 30, where it can be seen RL potential reduction from 20 531 m3/year to 13 531 m3/year, being the main component of this reduction the losses in the connections and not in the network itself.

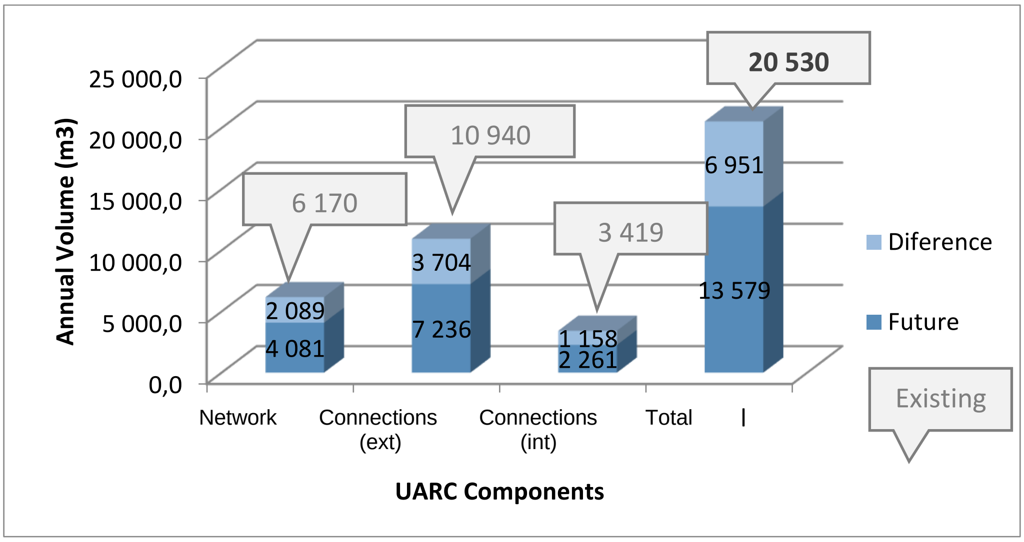

Fig. 30 – UARL Components – Gaula WDS

As verified in Table 6, Real losses in Gaula's system in 2018 represented 79% of total water entering the system, corresponding to 434 273 m^3. Considering the value of Unavoidable Annual Real Losses previously obtained to the existing situation, 20 530 m^3, Infrastructure Leakage Index comes to a value much higher than 4 (434 273 / 20 530), revealing that network is in a very bad shape having a huge potential of real losses reduction. Apparent Losses volumes are significantly lower than Real Losses, nonetheless, these volumes must not be ignored. Most pf Apparent Losses values result of measurement devices errors, meaning that in order to control them those devices must be appropriated to the predicted volumes passing through them, and its age [21].

Fig. 31 shows measurement device's age influence in measurement errors, easily reaching error values of 10%. In Santa Cruz WDS study it was considered as Apparent Losses a value of 20% of the Consumptions in each subsystem. This value is higher than the commonly verified but, in this case, it has no relevance in the overall volume since Real Losses have such a high value. In conclusion, the oldest measurement devices and/ the ones controlling significant consumptions must be the first ones analysed and replaced when necessary.

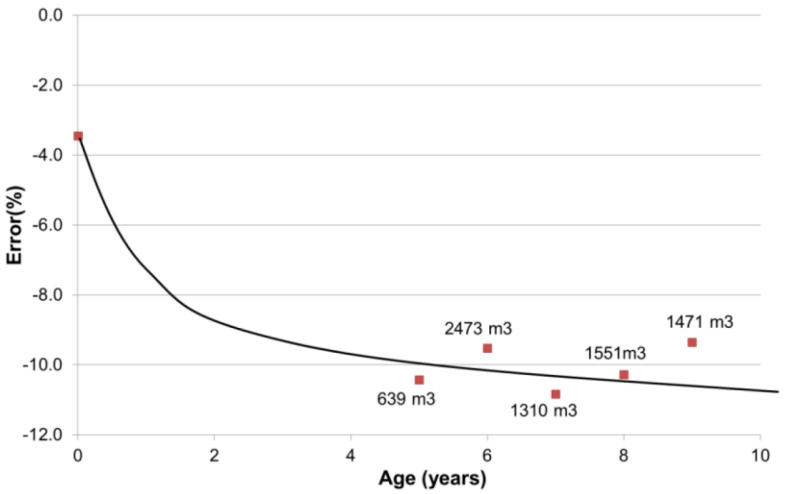

Fig. 31 – Domestic Flow Measurement Device's Age influence in the measured value [21].

A brief analysis of Santa Cruz Municipality flow meters resulted in the results presented in Fig. 32 and Table 13, where it can be concluded that the devices' average age is 11 years old being 25% of the devices older than 15 years old.

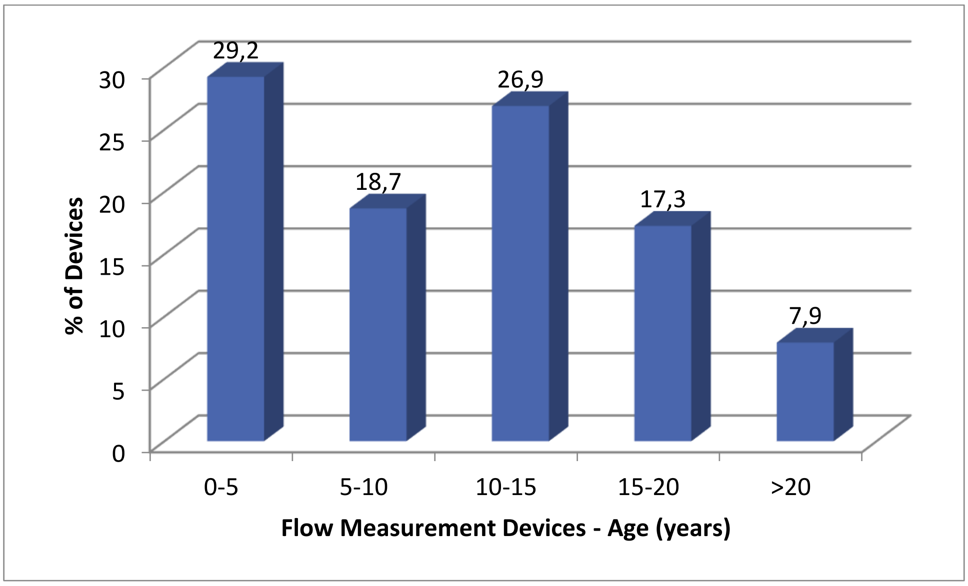

Fig. 32 – MSC - Flow Meters Distribution Age

In addition to the older sate of the refered devices, according to MSC data, most of the Significant Consumers have really old devices, being the resulting measured values really different than the real ones, being presented in Table 13 MSC 10 most Significant Consumers devices' age.

Table 13 -Most Significant Flow Meters' age in MSC

Consumer (#)	Consumption (m^3)	Age (years)
1	51.662	23,6
2	47.810	3,3
3	31.351	27,8
4	29.998	20,4
5	20.686	11,8
6	19.790	12,4
7	13.153	14,8
8	12.543	20,4
9	7.519	16,8
10	7.253	13,8

It must be noted that Santa Cruz most Significant Consumers represent only 0,05% of the total number of consumers, but this low percentage of consumers corresponds to 10% of Municipality total consumption, according to the provided data, representing twice the billed consumption of the studied subsystem Gaula. Also, from Table 13 data it can be observed that indicated measurement device's average age is 17 years old, meaning that considering a 20% error in their measurements, there are 60 000 m^3 of annual Apparent Losses associated to these consumers.

Fig. 33 presents percentual relation between Santa Cruz Municipality's Consumers and consumption, being once again reenforced that a few number of consumers are responsible for higher consumption values, being the errors related to their measurement devices the origin of considerable Apparent Losses Volume. In the graphic bellow it can be observed that only 1% of the Municipality consumers are responsible for 20% of the consumed water volume.

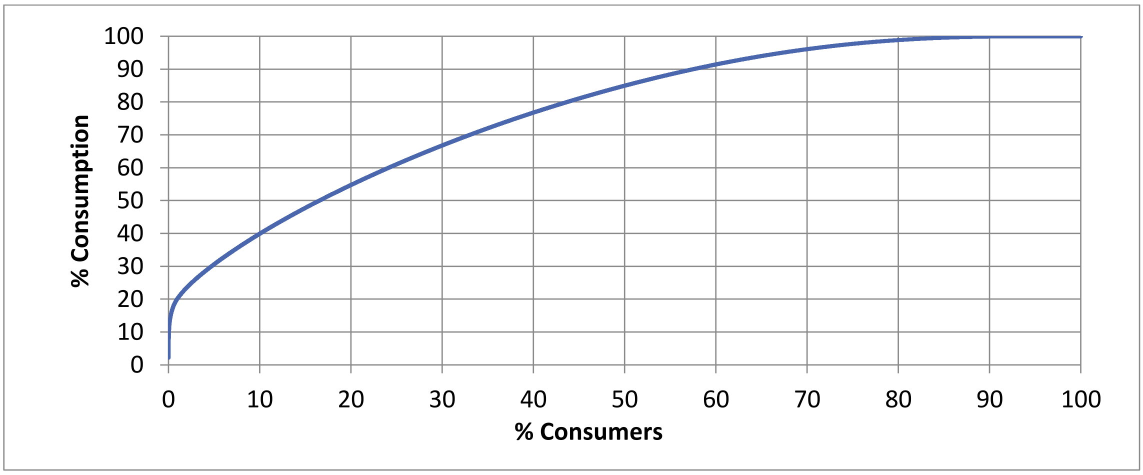

Fig. 33 – Consumers/Consumption Percentual relation

Unbilled authorized consumption, corresponding to the volumes used by the municipality itself, couldn't be analysed since no data was provided. These values must be measured and not estimated and the needs for irrigation must be analysed, to adjust eventual wasted volumes.

4.5 Water-Energy Nexus in Santa Cruz WDS

4.5.1. Water and Energy Balance

Gaula WDS's analysis and parameters previously described were applied to each one of Santa Cruz WDS sub-subsystems. In the analysis it was considered not only the existing conditions and network characteristics, but also Influence Areas reformulation, management of existing energy levels and creation of new ones and sectorization of the network with creation of ZMAs. Pressure values in average, peak and static scenarios can be seen in Fig. 34, Fig. 35 and Fig. 36.

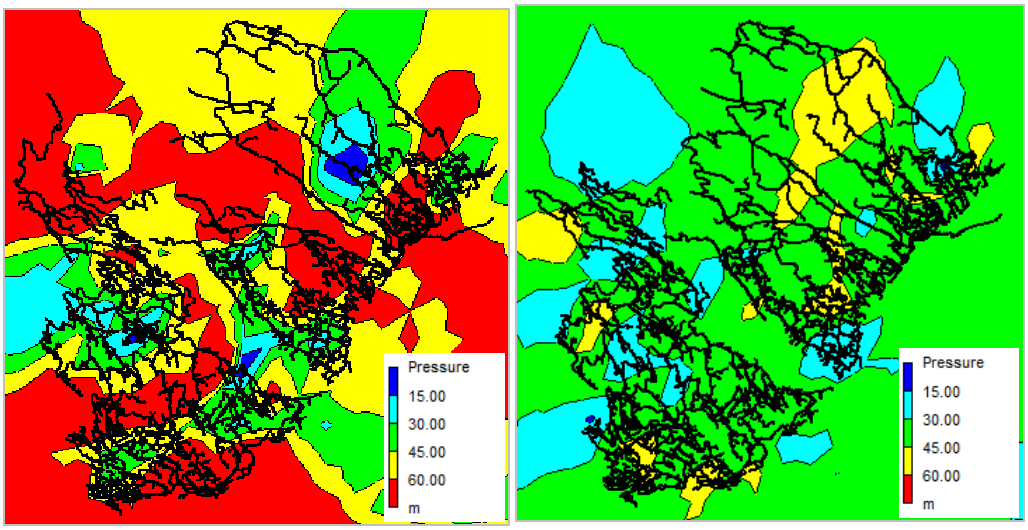

Fig. 34 – Santa Cruz – Average Scenario (Existing Situation/RSS Proposed Situation)

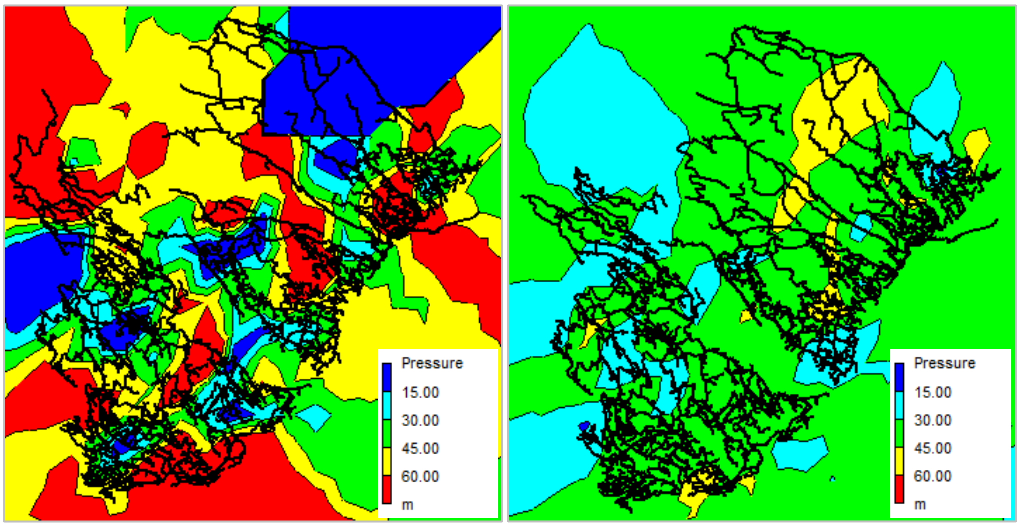

Fig. 35 – Santa Cruz – Peak Scenario (Existing Situation/RSS Proposed Situation)

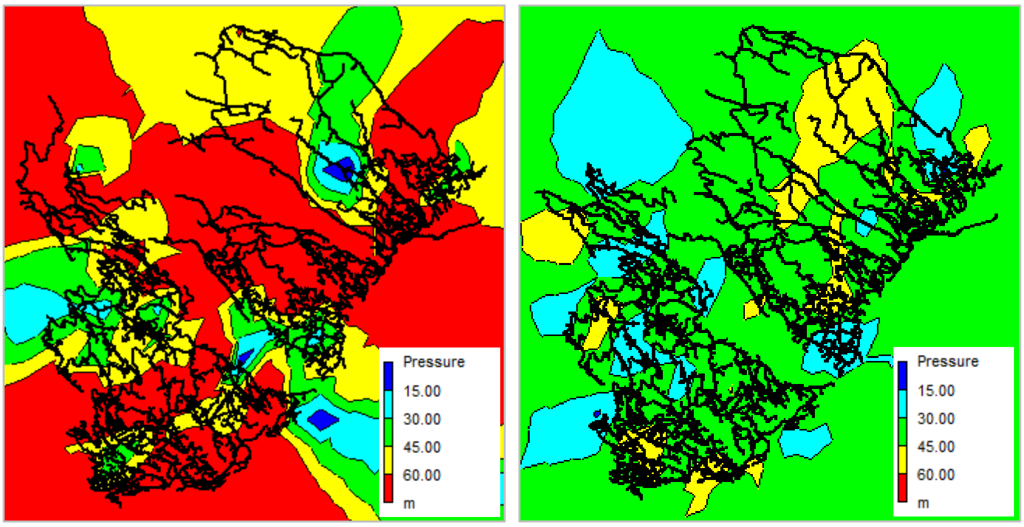

Fig. 36 – Santa Cruz – Maximum Pressure Scenario (Existing Situation/RSS Proposed Situation)

Table 14 shows a comparison between the volumes verified in the year considered as the existing situation (2018), the year when the proposed changes were finished and the hypothetical target to be achieved according to PEAASAR II.

Table 14 – Annual Volumes – Santa Cruz Municipality

Situation	Total Volume (m^3)	Billed Volume (m^3)	Unbilled Volume (m^3)	UV/TV (%)
Existing situation (2018)	10 123 027	2 558 487	7 564 540	74.7%
Target (PEAASAR II)	3 009 821	2 558 487	451 334	15.0%
Difference	7 113 206	-	7 113 206	-
Proposed Scenario	6 778 348	2 558 487	4 219 861	62.3%
Difference	3 344 679	-	3 344 679	-

In the accomplished results presented in the table above it was considered that consumptions wouldn't change. The volume presented in the existing situation was provided by Santa Cruz Municipality and applied to the hydraulic model. The "proposed scenario" volumes were generated by the hydraulic model with the changes proposed in the project executed by RSS.

As conclusion, implementing the solutions in the hydraulic system proposed by RSS would not only reduce the existing pressures, as presented before, but also allow an Unbilled Volume reduction of 44%, corresponding to a 33% reduction, or 3 344 679 m^3 of Total Volume entering Santa Cruz hydraulic system.

Also, even correcting the hydraulic network that due to the population growth was not working properly, there would still be a huge percentage of water losses in the system, meaning that applying active leakage control measures and controlling al the system's volumes, it would be possible to reduce water losses values to values closer to PEAASAR target, saving considerable amounts of this natural resource.

Reducing the water volume entering the system implies energy savings as well, since from the moment it is extracted from its source until it is available for consumption, water goes through several processes that require energy consumption, in processes as its extraction, transportation or treatment.

Portuguese Island, contrarily to what happens in the remaining country with ERSAR (Entidade Reguladora dos Seviços de Águas e Reíduos/Water and Waste Water Regulatory Entity), has no regulatory entity to control and analyse and publicly provide water system's values and indexes. Therefore, in order to estimate energy savings corresponding to the water saved, values from ERSAR 2018 report were considered.

To estimate an average value of energy consumed per m^3 entering the system, it was considered all Portuguese municipalities data of Water distribution systems with validated annual values of energy consumption and entering water in its systems.

As shown in detail in Appendix II, the total annual entering volume of the selected municipalities in 2018 (the last year with complete data information when the hydraulic model was developed), was 745 452 453 m^3, and the annual energy consumption was 265 893 452 kWh, meaning the average energy consumption per cubic meter of water entering the system, estimated according to 2018 data, was 0,36 kWh/m^3.

Considering Table 14 data and the average annual energy consumption value estimated of 0,36 kWh/m^3 of water entering the system, it can be reached an estimated value of 1 204 084 kWh of energy saved per year resulting from RSS proposed changes in MSC WDS, and 2 560 754 kWh per year if PEAASAR goal was eventually reached.

4.5.2. PAT Implementation

In the present chapter it will be studied the possibility of implementing turbine in strategical locations in order to improve the efficiency of Santa Cruz Network, taking advantage of the modifications in the WDS already planned to improve the system's efficiency and hydraulic behavior with the implementation of micro-hydro technology. Being the existing reservoirs working with no control devices, the introduction of some Flow Control Valves (FCV) upstream the existing tanks was considered in RSS proposition. With the implementation of this devices, water volumes will enter the tanks through a constant flow during a certain period of time, avoiding high pressure variations and pipe breaks. Regulating pressures upstream the reservoirs through a continuous entering flow in the reservoirs has no impact in the foreseen water losses over the years, being the only changing variable will be the duration of the valve in an open status.

Table 15 presents FCV considered in RSS study, which will be located upstream the existing tanks to regulate the existing entering flows. This change in WSS was designed to not only control the entering flows but also regulate pressures in those locations. The goal of the following calculation is to understand the viability of turbine implementation in two pilot locations, since the cost associated to the exceeding elements not predicted in RSS study would easily dissipate in the overall cost and the result energy could be sold or used resulting in additional saving costs.

Table 15 – FCV calibration in RSS Santa Cruz WDS Proposal

ID	DN (mm)	Q (l/s)	ΔH (m)	QxΔH
QG	**150**	**23,0**	**43,47**	**999,81**
CB	80	7,5	59,1	444,432
PE	80	6,0	50,29	301,74
MV	80	7,0	37,84	264,88
RL	80	7,0	27,75	194,25
AB1	65	4,0	45,76	183,04
RS	80	3,0	50,11	150,33
PC	65	2,0	42,71	85,42
CO	80	2,5	29,22	73,05
RO	65	1,5	46,69	70,035
MOI	80	2,0	27,56	55,12
EI	65	1,5	29,66	44,49

Having turbines working as FCV, they will work in perfect conditions, meaning that the turbomachine will work in conditions with constant flow and head values. Also, with the predicted water volumes reduction resulting from Active Leakage Control, the only characteristic changing in the device during this losses evolution would be its daily working duration, meaning that the turbine would work in the same conditions of flow and head, but in a shorter time duration per day. The FCV to be studied will be the one with higher value of "Qx△H", located upstream of Quinta do Garajau Tank (QG).

According to the available head and flow, the chosen PAT for Quinta do Garajau, was Etanorm 65-250, which characteristic curve is shown in Fig. 37.

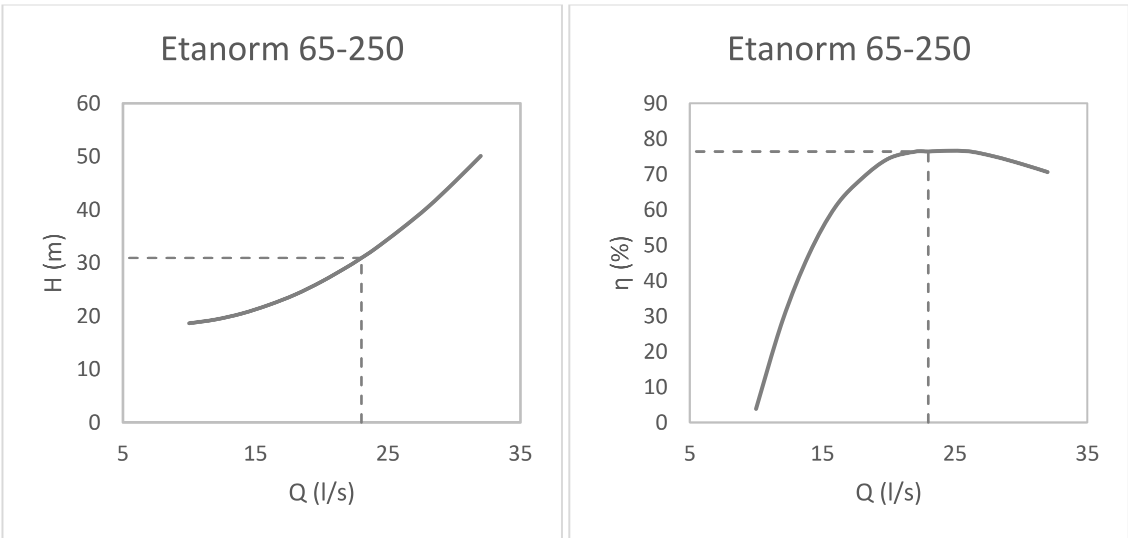

Fig. 37 – Characteristic curve of the PAT Etanorm 65-250

Implementing the PAT in the hydraulic model and considering a Hydraulic Regulation (HR) operation strategy, the obtained results were the ones shown in Fig. 38. Being the Best Efficient

Point (BEP) near to the 23 l/s flow stablished in RSS study, it was only necessary to guarantee enough pressure dissipation (through an upstream PRV) to assure 31m of headloss available for the PAT.

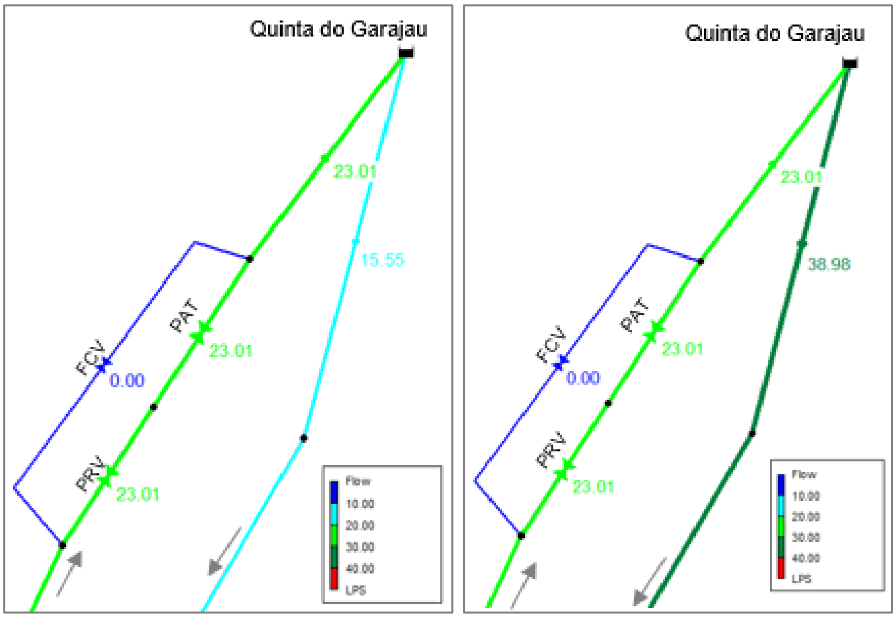

Fig. 38– EPANET Hydraulic Model – Results in Average (left) and Peak (right) scenarios

To simulate the selected PAT in *EPANET* hydraulic model, a General-Purpose-Valve (GPV), was inserted with PAT's characteristic curve associated, as shown in Fig. 39.

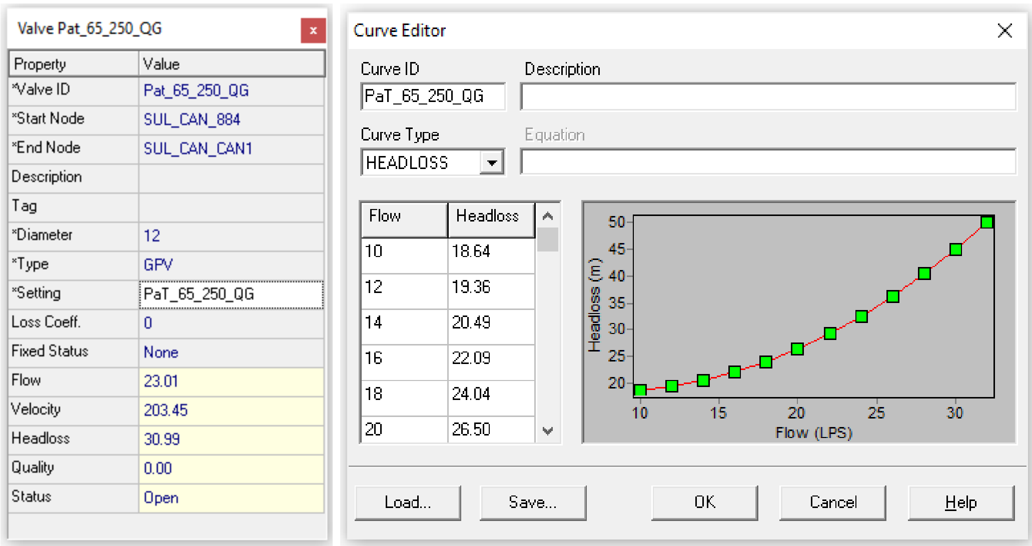

Fig. 39– EPANET Hydraulic Model – PAT characteristics (left) and PAT Characteristic Curve (right)

Since there was no consumption pattern available, it was considered as an approximation that the system would work 4 hours in peak scenario, 12 hours in average scenario and 8 hours with no consumption but with an outflow corresponding to the network's Real Losses. In Table 16 it's presented the outflows, divided by real losses and consumptions including Apparent Losses.

Table 16 – Quinta do Garajau Partial Outflows – RSS Proposal

Quinta do Garajau Reservoir Volume	(m3)	1000
Outflow (average Scenario)	(l/s)	15.55
Consumption + Ap.Losses (average scenario)	(l/s)	11.14
Outflow (peak Scenario)	(l/s)	38.98
Consumption + Ap.Losses (peak scenario)	(l/s)	34.54
Real Losses Component	(l/s)	4.41

In the study of Quinta do Garajau behavior through the inflows and outflows, an iterative process was made to understand how many daily hours the PAT would have to work to assure that there would be no overflows or lack of water available volume, considering that the working period of the turbomachine would occur with no interruptions.

Table 17 – PAT Working Time Simulation - Iterative Process

WDS Scenario	Simultion Time (h)	Inflow (m3)	Outflow (m3)	Reservoir Volume	PAT Working Time (h)
Real Losses	1	0.0	15.9	850.0	0
Real Losses	2	0.0	15.9	834.1	0
Real Losses	3	0.0	15.9	818.2	0
Real Losses	4	0.0	15.9	802.4	0
Real Losses	5	0.0	15.9	786.5	0
Real Losses	6	0.0	15.9	770.6	0
Peak	7	82.8	140.3	713.1	1
Peak	8	82.8	140.3	655.6	1
Average	9	82.8	56.0	682.5	1
Average	10	82.8	56.0	709.3	1
Average	11	82.8	56.0	736.2	1
Average	12	82.8	56.0	763.1	1
Average	13	82.8	56.0	789.9	1
Average	14	82.8	56.0	816.8	1
Average	15	82.8	56.0	843.6	1
Average	16	82.8	56.0	870.5	1
Average	17	82.8	56.0	897.3	1
Average	18	82.8	56.0	924.2	1
Average	19	82.8	56.0	951.1	1
Average	20	82.8	56.0	977.9	1
Peak	21	82.8	140.3	920.4	1
Peak	22	82.8	140.3	862.9	1
Real Losses	23	34.7	15.9	881.8	0.4
Real Losses	24	0.0	15.9	865.9	0.0
TOTAL	*24*	*1360.1*	*1360.1*	*19 724.0*	*16.4*

According to the previous simulation, the PAT would have to work 16 hours and 24min per day with a volume of 1360,1 m^3 per day, corresponding to an annual volume of 496 436,5 m^3 passing through the proposed turbine.

4.5.3. Energy Production and PAT Cost

To develop an economic analysis, to be studied in the next chapter, the energy production must be determined. This variable will depend on the system's flows and daily demand patterns that, in this case, due to lack of information, it was considered the assumption previously described, and can be calculated according to equation [7]:

$$E = \sum \eta \gamma Q H \Delta t = \sum P_u \Delta t \qquad [7]$$

where E represents energy (kWh), P_u is Power (kW) and Δt is the time interval (h). [23]

In this particular case, PAT was installed in ideal conditions, meaning that it will work with an almost constant flow (Q), head (H) and rotation speed (N) value, being those values: Q=23l/s; H=31m and N=1520r.p.m. The resultant power and energy production, according to the presented data are shown in Table 18.

Table 18 – Annual Energy Production

Q (l/s)	23.01
H (m)	30.99
(-)	0.74
Pu (kW)	5.2
t	16.4
E (kWh/day)	84.8
E (MWh/year)	31.1

It's worth to mention it would be produced green energy, being not only responsible for null CO_2 emissions in the production process, but also, when consumed the green energy instead of the usual energy produced by pollutant sources, it would avoid more than 18 000kg of CO_2 emissions. There is a relation between energy consumed in the network and CO_2 emissions of 582 to 877 g CO_2/kWh [23].

The cost of hydropower scheme was estimated based on Fig. 40 where unit cost per rated power are presented and from where it is concluded that a complete hydropower scheme with a PAT with approximately 5kW of power would cost 3000€/kW, reaching a total cost of 15000€ for the hydropower scheme.

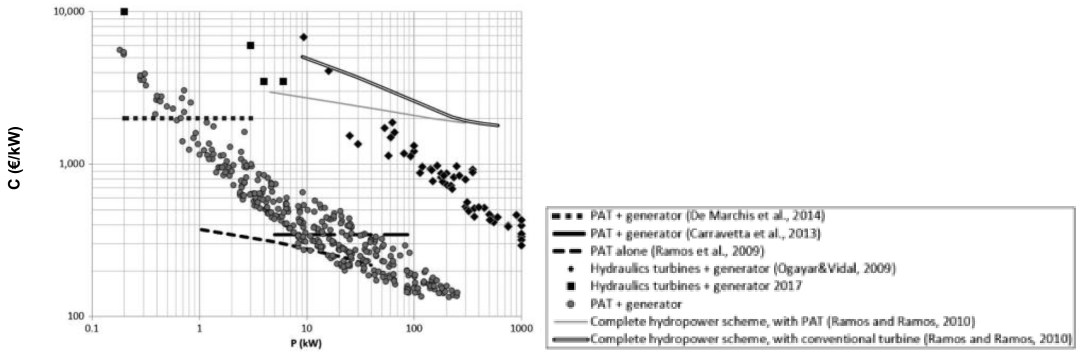

Fig. 40 – PAT Unit Cost per Rated Power [40]

5. ECONOMICAL ANALYSIS

5.1 Water and Energy Savings

In the following it will be presented an economical study considering the avoidable costs due to not only leakage control in Santa Cruz hydraulic system, but also including hydropower schemes benefits.

With the development of digital twins, it is possible, comparing both built scenarios, to determine the approximate value of losses and the resulting costs and savings. In the further calculations it was considered an average value of buying and selling water of, respectively, 0.2954€/m^3 and 0.8502€/m^3, according to the data provided by Santa Cruz Municipality.

In the estimation of economical savings as a consequence from reduction of water losses, it was assumed that the consumption volumes would not change, and the apparent losses represent 20% of the consumption values. Also, it was applied the buying cost for real losses water volumes and the average selling price to the apparent losses. Therefore, the resulting savings for Santa Cruz Municipality are the ones presented in Table 19.

Table 19 – Water and Energy Savings in Santa Cruz WDS

Description	Total Values (TV)	Billed Values (BV)	Unbilled Values (UV)	UV/TV (%)
Existing situation Volume (2018) (m3)	10 123 027	2 558 487	7 564 540	74.70%
Target Volume (PEAASAR II) (m3)	3 009 821	2 558 487	451 334	0
Difference Volume (m3)	7 113 206	-	7 113 206	-
Water Savings (€)	2 536 286	435 045	2 101 241	
Energy Savings (kWh/year)	2 560 754	0	2 560 754	
Energy Savings (€)	250 953.91	0.00	250 953.91	
RSS Proposed Scenario Volume (m3)	6 778 348	2 558 487	4 219 861	62.30%
Difference Volume (m3)	3 344 679	-	3 344 679	-
Water Savings (€)	1 423 065	435 045	988 018	
Energy Savings (kWh/year)	1 204 084	0	1 204 084	
Energy Savings (€)	118 000.28	0.00	118 000.28	

To determine energy savings an energy cost of 0.098€/kWh, corresponding to year 2018, based on ERSE (Entidade Reguladora dos Serviços Energéticos / Energetic Services Regulatory Entity) data.

Therefore, the 1 204 084 kWh/year of saved energy previously determined resulting from RSS proposed Santa Cruz hydraulic model changes, would represent a value of 118 000 € saved every year only from water that wouldn't have to be wasted in Santa Cruz WDS.

If the same method was applied to PEAASAR goal of reducing losses to 15% of the total water volume entering the system, it would lead to an annual saved value of 250 954€, corresponding to 2 560 754 kWh.

Both water and energy together would lead to more than 1,5M€ annually saved, resulting mainly from pressure regulation and old pipelines replacement and adjustment to the new population data.

5.2 Benefits of Energy Production

In this chapter it will be analyzed the economic viability of PAT implementation in Santa Cruz water network, considering only the recovered energy as a source of income, meaning that no costs or benefits from water losses and savings previously mentioned will be taken into account.

For this economic analysis a 20 year period was considered, corresponding to the lifetime of a PAT. It was considered a 2% of installation cost as annual maintenance costs and 3 different discount rates: 6%, 8% and 10%.

Energy's value was considered as 0,098€/kWh, from ERSE database, since all the hydraulic model development was made from Santa Cruz 2018 water balance values.

Energy benefits main results are presented in Table 20, being the full calculation data presented in Appendix IIII

Table 20 – Economical Analysis Main Results

Initial Investment Cost (€)	15 000.00				
Annual Maintenance Cost (€)	300.00				
Annual revenue (€/year)	3 050.74				
Discount Rate	6%	8%	10%		17.62%
NPV (€)	16 550.8	12 007.2	8 418.6		0.0
B/C (-)	7.5	9.1	11.2		26.3
Payback Period (years)	7	8	9		IRR

According to the presented results an average of 10 years would be necessary to payback the investment in the hydropower technology, considering its installation independent from the remaining changes of Santa Cruz water network. Also, this is a pessimistic approach, since in the present year, 2022 energy cost would represent a higher value, resulting in higher value of annual revenue and consequently a lower payback period.

An integration of renewable energy benefits in the overall plan of Santa Cruz water network rehabilitation will be presented in the next chapter.

Finally, the environmental benefit resulting from the implementation of this solution should be emphasized, since this investment would lead to more than 18 tons of CO_2 emissions saved every year, due to this new green electrical consumption source.

It was studied only one location for implementation of an hydroelectrical solution, but all the reservoirs upstream valves and network's PRV should be studied, to create other sources of green energy produced from existing energy dissipating devices.

5.3 Overall Benefits

To begin the present chapter, it will be analysed RSS Water Losses Study, considering the estimated costs and estimated savings. According to RSS data, it would be necessary a duration of 2 years and an estimated investment of 13 800 000,00€ to apply the proposed changes to Santa Cruz network, with a total extension of 437km, including pipeline replacement, introduction of new pressure regulation devices and calibration of the existing ones, introduction of flow meters and other eventual necessary works.

This estimated investment, in the worst-case scenario, would be recovered after a maximum of 10 years when considered the cost resulting from water savings presented in Table 19 (1 423 065 €/year). Once again this is a pessimistic scenario since it considers the immediate savings resulting from replacing existing pipes responsible for some water leakage. The implementation of the present study coordinated with active leakage control measures could reach, in a limit situation, a period of investment return of 5,5 years, corresponding to the 2 536 268 €/year saved, and to more than 7Mm^3 water every year.If to the previous limit scenario energy savings would also be considered, a value of 2 787 240€ would be saved every year, reducing the return period to less than 5 years and avoiding more than 500 ton of CO_2 emissions.

Analysing the integration of hydropower solutions in the overall project, it should be considered, firstly the impact of the previously studied solution in the corresponding WDS, Quinta do Garajau. In RSS estimation costs to Santa Cruz water system rehabilitation, a value of 42 000€ was reached to the mentioned sub-system. This estimation includes a flow control valve (FCV) to regulate flow entering in the reservoir and all the construction related kind of works, meaning that only the turbomachine price would be added to the present cost estimation. Fig. 40 shows that turbomachine alone would have a cost of 1100€, representing less than 3% of the estimated cost for this subsystem, and being recovered in less than a year due to its consequent annual energy saving costs. If several energy recovering solutions were implemented in the system return of the investment period would reduce significantly, since as it was shown the differential cost of solutions' implementation has no relevance in the overall cost but has significant environmental and economic benefits. Finally, in this analysis it was not included the indirect saved costs, that needed to be fixed before the hydraulic system's restructuration, being that value much lower now due pressure regulation.

6. CONCLUSIONS AND FUTURE WORK

6.1 Final Conclusions

In the present work it was studied water supply and distribution systems of Santa Cruz, in the Portuguese Madeira Island, where Pumps working as Turbines (PAT) technology was implemented upstream of an existing reservoir, achieving the same performance as the designed Flow Control Valve (FCV) complementing its functions with renewable energy production. This energy study was only possible after a pressure regulation methodology, since the saved water consequent from this approach would be economically and environmentally better than taking advantage of excessive pressures to produce energy.

Pressure reduction study was performed in the Hydraulic Systems Company RSS, whose project was developed directly to Santa Cruz Municipality, being a real case-study to be implemented.

In terms of water balance, after the implementation of RSS proposal, there would be 3 344 679m^3 annually saved, representing 1 204 084 kW/h annual energy savings, an estimated economical saving of more than 1.5M€ and more than 530ton/year of CO_2 emissions saved. Also, if active leakage control was performed and eventually PEAASAR target would be achieved, it would represent an estimated annual saving value of mor than 2.7M€ and more than 7M m^3 of water saved.

Also, the studied source of renewable energy upstream the reservoir, would have an insignificant cost, when included in in the overall network reformulation, achieving a considerable amount of energy recovered, saving 3 050€/year and 18 ton/year of CO_2 emissions.

In conclusion, due to the development of a Digital Twin, Municipality of Santa Cruz is now able to know its system, identify its weaknesses and locate and fix the hydraulic problems, in order to solve the excessive pressure overall scenario, lack of supply to some costumers, and periodical ruptures happening in the system.

6.2 Future Work Suggestions

Since FCV are considered in RSS study upstream of each gravity supplied reservoirs of Santa Cruz WSS and, being the location characterized for having high slopes, all FCV and the most relevant PRV should be studied in future works, in parallel with systems behavior in hydrotransient conditions, in order to maximize the potential of energy recovery in the system. This renewable energy feasible solutions should be implemented at the same time as the hydraulic network's changes, in order to minimize its costs.

Also, since this work is part of a main Project, it would be interesting to integrate data uploaded by the flow and pressure devices intended to install in the real network, and develop an improved version of the DT developed in this work where the real time data could be integrated in real time.

7. BIBLIOGRAPHY

[1]	Shiklomanov I.A. - Appraisal and Assessment of World Water Resources, Water International, 25:1, 11-32; 2000
[2]	Ramos H., Covas D., Araujo L., Mello M. - Available energy assessment in water supply systems," 31st IAHR Congr., Water Eng. Futur. Choices Challenges, pp. 1050–1060, 2005.
[3]	Agência Portuguesa do Ambiente (APA), Plano Nacional da Água, 2015, https://www.apambiente.pt/ https://www.apambiente.pt/_zdata/Politicas/Agua/PlaneamentoeGestao/PNA/2015/PNA2015.pdf) consulted in 2019
[4]	Lambert A., Hirner W. - Losses from Water Supply Systems: Standard Terminology and Recommended Performance Measures, *IWA blue pages*, vol. October, no. 3, pp. 1–13, 2000.
[5]	Lambert, A.O - International Report: Water Losses Management and techniques, Water Science and Technology: Water Supply, vol.2, Iss.4, 2002/9
[6]	Petroulias, N., Foufeas, D., Bougoulia, E. - Estimating water losses and assessing network management intervention scenarios: the case study of the water utility of the city of Drama in Greece. Procedia Engineering, 162, 559–567,2016
[7]	Vilanova M.R.N., Balestieri J.A.P. - Energy and hydraulic efficiency in conventional water supply systems, Elsevier, 2014
[8]	Lambert A.O., Brown T.G., Takizawa M., Weimer D. - A Review of performance indicators for real losses from water supply systems, J Water SRT, Aqua Vol.48, Nº6, pp. 227-237, 1999
[9]	Monsef H., Naghashzadegan M., Fermani R., Jamali A., Pressure management in water distribution systems in order to reduce energy consumption and background leakage, IWA Publishing, Journal of Water Supply, 2018
[10]	Germanopoulos G., Jowitt P. W. - Leakage reduction by excess pressure minimizion in a water supply network, Proc.. Instn. Civ. Engrs, Part 2, 195-216, 1989
[11]	Galdiero E., Paola F., Fontana N., Giugni M., Savic D. - Decision support system for the optimal design of district metered areas, Journal of Hydroinformatics, 18.1, 2016
[12]	S. Parra, S. Krause, F. Krönlein, F. W. Günthert, T. Klunke, - Intelligent pressure management by pumps as turbines in water distribution systems: results of experimentation,- Water Sci. Technol. Water Supply, vol. 18, no. 3, pp. 778–789, 2018
[13]	I. F. García, D. Novara, A. M. Nabola, - A model for selecting the most cost-effective pressure control device for more sustainable water supply networks, Water (Switzerland), vol. 11, no. 6, 2019
[14]	Berardi, L., Laucelli, D. B., Simone, A., Mazzolani, G., Giustolisi, O. (2016). Active leakage control with WDNetXL. Procedia Engineering, 154, 62–70, 2016
[15]	Özdemir O., - Water leakage management by district metered areas at water distribution networks, 2018

[16]	Gomes R., Sousa J., Sá Marques A., - Influence of future water demand patterns on the district metered areas design and benefits yielded by pressure management, Procedia Engineering, 70, 744 – 752, 2014
[17]	UNESCO - The United Nations World Water Development Report, Volume 1, 2014
[18]	Covas D., Ramos H., Graham N., Maksimovic C. - Application of hydraulic transients for leak detection in water supply systems, IWA Publishing, Water Science and Technology: Water Supply, Vol 4, No 5–6, pp 365–374, 2004
[19]	H. Hoff, Understanding the Nexus, Backgr. Pap. Bonn2011 Conf. Water, Energy Food Secur. Nexus., no. November, pp. 1–52, 2011
[20]	US Department of Energy, “The Water Energy Nexus: Challenges and Opportunities,” U.S. Dep. Energy, p. 238, 2014.
[21]	Bates B. C., Kundzewicz Z. W., W, S., Palutikof, J. P. - Climate Change and Water. Climate change and water, Journal of Molecular Biology, Vol 403 Iss. 1, Pages 1-10, 2010
[22]	Arregui F.J. , Gavara F.J., Soriano J., Cobacho R. - Analysis of domestic water meters field performance, Water Loss 2014 Conference, 2014
[23]	Ramos H. - Innovations in Water Management: Systems Efficiency and Energy Applications in the Water Sector, The Palgrave Handbook of Global Sustainability, 2021
[24]	Carravetta A., Giudice G., Fecarotta O., Ramos H. - Energy Production in Water Distribution Networks: A PAT Design Strategy, Springer Science, 2012
[25]	European Commission - https://ec.europa.eu/info/eu-regional-and-urban-development/topics/cities-and-urban-development/city-initiatives/smart-cities_en, 2020, consulted in 2020
[26]	Gold S., Hesse J. - Digital systems smarten up water networks, Phys.org. 2021, 2015, consulted in 2021.
[27]	Ramos H.M., McNabola A., López-Jiménez P.A., Pérez-Sánchez M. - Smart Water Management towards Future Water Sustainable Networks, Water2020, *12*(1), 58 2019.
[28]	Asín, A., Boyd, M. - Smart Water: pipe control to reduce water leakages in Smart Cities, http://www.libelium.com/smart_water_wsn_pipe_leakages/ , 2011, consulted in 2018
[29]	Sadeghioon A. M., Metje N., Chapman D. N., Anthony C. J. - SmartPipes: Smart Wireless Sensor Networks for Leak detection in Water Pipelines, Journal of Sensor and Actuator Networks, 2014
[30]	Boyle T., Giurco D., Mukheibir P., Liu A., Moy C., White S., Stewart R. - Intelligent Metering for Urban Water: A Review, Water 2013
[31]	WaterWorld - Digital Twins For Managing Water Infrastructure, ://www.waterworld.com/water-utility-management/smart-water-utility/article/14173219/digital-twins-for-managing-water-infrastructure, 2020

[32]	Giudicianni C., Herrera M., Nardo A., Adeyeye K., Ramos H.M. - Overview of Energy Management and Leakage Control Systems for Smart Water Grids and Digital Water. Modelling 2020
[33]	Fuertes P., Alzamora F., Carot M., Campos. J.C. - Building and exploiting a Digital Twin for the management of drinking water distribution networks, Urban Water Journal, P. 704-713 2020.
[34]	DHI - The Digital Twin: What Is It And How Can It Benefit The Water Sector?, https://blog.dhigroup.com/2019/06/06/the-digital-twin-what-is-it-and-how-can-it-benefit-the-water-sector/, 2019, consulted in 2021
[35]	Singh K., - Real Time Digital Twin Of Water Distribution Network, https://www.linkedin.com/pulse/real-time-digital-twin-water-distribution-network-keshvinder-singh, 2019 consulted in 2021
[36]	Boulo, P., - Digital Twinfrastructure: Delivering Maximum Value For The Water Industry https://www.linkedin.com/pulse/digital-twinfrastructure-delivering-maximum-value-paul, 2018, consulted in 2021
[37]	Tao F., Zhang H., Liu A., Nee A. Y. C, - Digital Twin in Industry: State-of-the-Art, IEEE Transactions on Industrial Informatics, vol. 15, no. 4, pp. 2405-2415, 2019
[38]	Manual Epanet – https://www.microimages.com/documentation/Tutorials/Epanet2UserManual.pdf
[39]	Araujo L.S., Ramos H., Coelho S. - Pressure Control for Leakage Minimization in water distribution systems Management Water Resources Management, 20: 133–149, 2006
[40]	Novara D., Carravetta A., McNabola A., Ramos H.M. - Cost Model for Pumps as Turbines in Run-of-River and In-Pipe Microhydropower Applications, American Society of Civil Engineers., 2019

Appendix

Appendix I– Hydraulic Model – Emmiter Iterative Calculation

Iteration Number		1		2		3		4		5	
MSC Provided Values		(m3/y)	(l/s)	(m3/y)	(l/s)	(m3/y)	(l/s)	(m3/y)	(l/s)	(m3/y)	(l/s)
Volume Reservoir		548 286.00	17.39	548 286.00	17.39	548 286.00	17.39	548 286.00	17.39	548 286.00	17.39
Consumption A. Losses		95 011.00	3.01	95 011.00	3.01	95 011.00	3.01	95 011.00	3.01	95 011.00	3.01
R. Losses		434 272.80	13.77	434 272.80	13.77	434 272.80	13.77	434 272.80	13.77	434 272.80	13.77
Digital Twin Values		(m3/y)	(l/s)	(m3/y)	(l/s)	(m3/y)	(l/s)	(m3/y)	(l/s)	(m3/y)	(l/s)
Volume Reservoir		682 439.04	21.64	557 241.12	17.67	534 219.84	16.94	530 120.16	16.81	529 489.44	16.79
Consumption A. Losses		95 011.00	3.01	95 011.00	3.01	95 011.00	3.01	95 011.00	3.01	95 011.00	3.01
R. Losses		587 428.04	18.63	462 230.12	14.66	439 208.84	13.93	435 109.16	13.80	434 478.44	13.78
Ci= RL(MSC)/RL(Simul)		0.73928		0.93952		0.98876		0.99808		0.99953	
ID_Nó	∑ 0.5 Lij	E1=C0 ∑ 0.5 Lij		E2=E1.C1		E3=E2.C2		E4=E3.C3		E5=E4.C4	
GA1	29.03381	0.00029		0.00021		0.00020		0.00020		0.00020	
GA2	19.39405	0.00019		0.00014		0.00013		0.00013		0.00013	
GA3	7.49337	0.00007		0.00006		0.00005		0.00005		0.00005	
GA4	2.82146	0.00003		0.00002		0.00002		0.00002		0.00002	
GA5	21.39621	0.00021		0.00016		0.00015		0.00015		0.00015	
GA6	2.28339	0.00002		0.00002		0.00002		0.00002		0.00002	
GA7	41.19337	0.00041		0.00030		0.00029		0.00028		0.00028	
GA10	52.24877	0.00052		0.00039		0.00036		0.00036		0.00036	
GA11	17.47499	0.00017		0.00013		0.00012		0.00012		0.00012	
GA12	78.23710	0.00078		0.00058		0.00054		0.00054		0.00054	
GA13	50.37777	0.00050		0.00037		0.00035		0.00035		0.00035	
GA14	0.73351	0.00001		0.00001		0.00001		0.00001		0.00001	
GA15	34.72622	0.00035		0.00026		0.00024		0.00024		0.00024	
GA16	31.87000	0.00032		0.00024		0.00022		0.00022		0.00022	
GA17	14.91804	0.00015		0.00011		0.00010		0.00010		0.00010	
GA18	13.50000	0.00014		0.00010		0.00009		0.00009		0.00009	
GA19	12.14000	0.00012		0.00009		0.00008		0.00008		0.00008	
GA20	40.87000	0.00041		0.00030		0.00028		0.00028		0.00028	
GA26	38.56246	0.00039		0.00029		0.00027		0.00026		0.00026	
GA27	1.21858	0.00001		0.00001		0.00001		0.00001		0.00001	
GA28	1.29627	0.00001		0.00001		0.00001		0.00001		0.00001	
GA29	2.09313	0.00002		0.00002		0.00001		0.00001		0.00001	
GA30	0.28290	0.00000		0.00000		0.00000		0.00000		0.00000	
GA31	1.02127	0.00001		0.00001		0.00001		0.00001		0.00001	
GA32	1.91981	0.00002		0.00001		0.00001		0.00001		0.00001	
GA33	34.41377	0.00034		0.00025		0.00024		0.00024		0.00024	
GA34	86.03288	0.00086		0.00064		0.00060		0.00059		0.00059	
GA35	1.76375	0.00002		0.00001		0.00001		0.00001		0.00001	
GA38	53.88726	0.00054		0.00040		0.00037		0.00037		0.00037	
GA39	29.74254	0.00030		0.00022		0.00021		0.00020		0.00020	
GA41	3.25434	0.00003		0.00002		0.00002		0.00002		0.00002	
GA43	0.89511	0.00001		0.00001		0.00001		0.00001		0.00001	
GA44	0.02985	0.00000		0.00000		0.00000		0.00000		0.00000	
GA45	0.02009	0.00000		0.00000		0.00000		0.00000		0.00000	
GA46	0.91755	0.00001		0.00001		0.00001		0.00001		0.00001	
GA47	4.63192	0.00005		0.00003		0.00003		0.00003		0.00003	
GA48	8.69854	0.00009		0.00006		0.00006		0.00006		0.00006	
GA49	98.05685	0.00098		0.00072		0.00068		0.00067		0.00067	
GA50	5.39637	0.00005		0.00004		0.00004		0.00004		0.00004	
GA51	5.75128	0.00006		0.00004		0.00004		0.00004		0.00004	
GA52	0.99816	0.00001		0.00001		0.00001		0.00001		0.00001	
GA53	167.84856	0.00168		0.00124		0.00117		0.00115		0.00115	

ID_Nó	∑ 0.5 Lij	E1=C0 ∑ 0.5 Lij	E2=E1.C1	E3=E2.C2	E4=E3.C3	E5=E4.C4
GA54	49.69000	0.00050	0.00037	0.00035	0.00034	0.00034
GA55	104.85808	0.00105	0.00078	0.00073	0.00072	0.00072
GA56	0.93327	0.00001	0.00001	0.00001	0.00001	0.00001
GA57	1.39279	0.00001	0.00001	0.00001	0.00001	0.00001
GA58	19.31403	0.00019	0.00014	0.00013	0.00013	0.00013
GA59	5.14094	0.00005	0.00004	0.00004	0.00004	0.00004
GA60	1.49863	0.00001	0.00001	0.00001	0.00001	0.00001
GA61	9.52850	0.00010	0.00007	0.00007	0.00007	0.00007
GA62	33.47044	0.00033	0.00025	0.00023	0.00023	0.00023
GA63	28.21471	0.00028	0.00021	0.00020	0.00019	0.00019
GA64	2.72094	0.00003	0.00002	0.00002	0.00002	0.00002
GA65	22.73500	0.00023	0.00017	0.00016	0.00016	0.00016
GA66	1.19179	0.00001	0.00001	0.00001	0.00001	0.00001
GA67	14.20623	0.00014	0.00011	0.00010	0.00010	0.00010
GA68	37.09744	0.00037	0.00027	0.00026	0.00025	0.00025
GA71	6.08688	0.00006	0.00004	0.00004	0.00004	0.00004
GA72	0.49914	0.00000	0.00000	0.00000	0.00000	0.00000
GA73	27.77017	0.00028	0.00021	0.00019	0.00019	0.00019
GA74	0.31111	0.00000	0.00000	0.00000	0.00000	0.00000
GA75	66.78716	0.00067	0.00049	0.00046	0.00046	0.00046
GA76	1.08975	0.00001	0.00001	0.00001	0.00001	0.00001
GA77	9.26000	0.00009	0.00007	0.00006	0.00006	0.00006
GA78	8.47723	0.00008	0.00006	0.00006	0.00006	0.00006
GA79	85.36107	0.00085	0.00063	0.00059	0.00059	0.00059
GA80	17.29900	0.00017	0.00013	0.00012	0.00012	0.00012
GA81	76.75327	0.00077	0.00057	0.00053	0.00053	0.00053
GA82	0.92304	0.00001	0.00001	0.00001	0.00001	0.00001
GA83	0.76094	0.00001	0.00001	0.00001	0.00001	0.00001
GA84	0.39801	0.00000	0.00000	0.00000	0.00000	0.00000
GA85	0.80344	0.00001	0.00001	0.00001	0.00001	0.00001
GA86	0.34986	0.00000	0.00000	0.00000	0.00000	0.00000
GA87	0.57304	0.00001	0.00000	0.00000	0.00000	0.00000
GA88	0.82727	0.00001	0.00001	0.00001	0.00001	0.00001
GA89	8.62109	0.00009	0.00006	0.00006	0.00006	0.00006
GA90	25.68055	0.00026	0.00019	0.00018	0.00018	0.00018
GA91	41.64031	0.00042	0.00031	0.00029	0.00029	0.00029
GA93	19.68268	0.00020	0.00015	0.00014	0.00014	0.00013
GA94	16.27978	0.00016	0.00012	0.00011	0.00011	0.00011
GA95	39.08176	0.00039	0.00029	0.00027	0.00027	0.00027
GA96	0.27828	0.00000	0.00000	0.00000	0.00000	0.00000
GA97	0.35025	0.00000	0.00000	0.00000	0.00000	0.00000
GA98	83.81042	0.00084	0.00062	0.00058	0.00058	0.00057
GA99	69.26100	0.00069	0.00051	0.00048	0.00048	0.00047
GA100	1.67566	0.00002	0.00001	0.00001	0.00001	0.00001
GA101	13.76238	0.00014	0.00010	0.00010	0.00009	0.00009
GA102	50.77678	0.00051	0.00038	0.00035	0.00035	0.00035
GA103	16.85535	0.00017	0.00012	0.00012	0.00012	0.00012
GA104	5.70344	0.00006	0.00004	0.00004	0.00004	0.00004
GA105	0.26359	0.00000	0.00000	0.00000	0.00000	0.00000
GA106	25.35070	0.00025	0.00019	0.00018	0.00017	0.00017
GA107	6.50996	0.00007	0.00005	0.00005	0.00004	0.00004
GA108	4.67064	0.00005	0.00003	0.00003	0.00003	0.00003
GA109	1.80336	0.00002	0.00001	0.00001	0.00001	0.00001
GA110	126.06667	0.00126	0.00093	0.00088	0.00087	0.00086
GA111	8.07006	0.00008	0.00006	0.00006	0.00006	0.00006
GA112	1.73163	0.00002	0.00001	0.00001	0.00001	0.00001

ID_Nó	∑ 0.5 Lij	E1=C0 ∑ 0.5 Lij	E2=E1.C1	E3=E2.C2	E4=E3.C3	E5=E4.C4
GA113	22.29937	0.00022	0.00016	0.00015	0.00015	0.00015
GA114	23.88682	0.00024	0.00018	0.00017	0.00016	0.00016
GA115	31.01019	0.00031	0.00023	0.00022	0.00021	0.00021
GA116	1.14917	0.00001	0.00001	0.00001	0.00001	0.00001
GA117	0.16708	0.00000	0.00000	0.00000	0.00000	0.00000
GA118	1.19158	0.00001	0.00001	0.00001	0.00001	0.00001
GA119	13.85576	0.00014	0.00010	0.00010	0.00010	0.00009
GA120	18.31705	0.00018	0.00014	0.00013	0.00013	0.00013
GA121	181.98500	0.00182	0.00135	0.00126	0.00125	0.00125
GA122	19.58157	0.00020	0.00014	0.00014	0.00013	0.00013
GA123	23.52318	0.00024	0.00017	0.00016	0.00016	0.00016
GA124	0.69730	0.00001	0.00001	0.00000	0.00000	0.00000
GA125	12.35730	0.00012	0.00009	0.00009	0.00008	0.00008
GA126	0.91260	0.00001	0.00001	0.00001	0.00001	0.00001
GA127	35.02951	0.00035	0.00026	0.00024	0.00024	0.00024
GA128	0.48760	0.00000	0.00000	0.00000	0.00000	0.00000
GA129	64.39343	0.00064	0.00048	0.00045	0.00044	0.00044
GA130	39.91970	0.00040	0.00030	0.00028	0.00027	0.00027
GA131	0.56640	0.00001	0.00000	0.00000	0.00000	0.00000
GA132	0.52178	0.00001	0.00000	0.00000	0.00000	0.00000
GA133	2.48000	0.00002	0.00002	0.00002	0.00002	0.00002
GA134	4.43000	0.00004	0.00003	0.00003	0.00003	0.00003
GA135	6.11329	0.00006	0.00005	0.00004	0.00004	0.00004
GA136	46.73763	0.00047	0.00035	0.00032	0.00032	0.00032
GA137	4.26666	0.00004	0.00003	0.00003	0.00003	0.00003
GA138	71.24144	0.00071	0.00053	0.00049	0.00049	0.00049
GA139	6.62433	0.00007	0.00005	0.00005	0.00005	0.00005
GA140	82.76423	0.00083	0.00061	0.00057	0.00057	0.00057
GA141	0.64348	0.00001	0.00000	0.00000	0.00000	0.00000
GA142	0.45234	0.00000	0.00000	0.00000	0.00000	0.00000
GA143	29.71530	0.00030	0.00022	0.00021	0.00020	0.00020
GA144	5.69881	0.00006	0.00004	0.00004	0.00004	0.00004
GA145	78.94378	0.00079	0.00058	0.00055	0.00054	0.00054
GA146	17.03096	0.00017	0.00013	0.00012	0.00012	0.00012
GA147	14.51437	0.00015	0.00011	0.00010	0.00010	0.00010
GA148	39.53001	0.00040	0.00029	0.00027	0.00027	0.00027
GA149	12.70802	0.00013	0.00009	0.00009	0.00009	0.00009
GA150	19.77486	0.00020	0.00015	0.00014	0.00014	0.00014
GA151	1.67400	0.00002	0.00001	0.00001	0.00001	0.00001
GA152	24.51533	0.00025	0.00018	0.00017	0.00017	0.00017
GA153	30.51478	0.00031	0.00023	0.00021	0.00021	0.00021
GA154	40.36177	0.00040	0.00030	0.00028	0.00028	0.00028
GA155	21.75131	0.00022	0.00016	0.00015	0.00015	0.00015
GA156	2.36036	0.00002	0.00002	0.00002	0.00002	0.00002
GA157	4.41803	0.00004	0.00003	0.00003	0.00003	0.00003
GA158	40.13199	0.00040	0.00030	0.00028	0.00028	0.00028
GA159	1.16747	0.00001	0.00001	0.00001	0.00001	0.00001
GA160	2.97987	0.00003	0.00002	0.00002	0.00002	0.00002
GA161	3.61955	0.00004	0.00003	0.00003	0.00002	0.00002
GA162	62.73030	0.00063	0.00046	0.00044	0.00043	0.00043
GA163	29.34777	0.00029	0.00022	0.00020	0.00020	0.00020
GA164	16.96895	0.00017	0.00013	0.00012	0.00012	0.00012
GA165	17.54019	0.00018	0.00013	0.00012	0.00012	0.00012
GA166	10.33913	0.00010	0.00008	0.00007	0.00007	0.00007
GA167	8.35911	0.00008	0.00006	0.00006	0.00006	0.00006
GA168	21.43766	0.00021	0.00016	0.00015	0.00015	0.00015

ID_Nó	∑ 0.5 Lij	E1=C0 ∑ 0.5 Lij	E2=E1.C1	E3=E2.C2	E4=E3.C3	E5=E4.C4
GA169	38.06637	0.00038	0.00028	0.00026	0.00026	0.00026
GA170	0.53403	0.00001	0.00000	0.00000	0.00000	0.00000
GA171	42.90468	0.00043	0.00032	0.00030	0.00029	0.00029
GA172	0.52243	0.00001	0.00000	0.00000	0.00000	0.00000
GA173	0.22743	0.00000	0.00000	0.00000	0.00000	0.00000
GA174	26.75513	0.00027	0.00020	0.00019	0.00018	0.00018
GA175	3.98691	0.00004	0.00003	0.00003	0.00003	0.00003
GA176	41.24111	0.00041	0.00030	0.00029	0.00028	0.00028
GA177	0.58584	0.00001	0.00000	0.00000	0.00000	0.00000
GA178	0.48309	0.00000	0.00000	0.00000	0.00000	0.00000
GA179	2.74965	0.00003	0.00002	0.00002	0.00002	0.00002
GA180	54.34545	0.00054	0.00040	0.00038	0.00037	0.00037
GA181	46.67343	0.00047	0.00035	0.00032	0.00032	0.00032
GA182	61.03257	0.00061	0.00045	0.00042	0.00042	0.00042
GA183	0.75990	0.00001	0.00001	0.00001	0.00001	0.00001
GA184	6.12118	0.00006	0.00005	0.00004	0.00004	0.00004
GA185	0.69061	0.00001	0.00001	0.00000	0.00000	0.00000
GA186	55.79127	0.00056	0.00041	0.00039	0.00038	0.00038
GA187	21.04526	0.00021	0.00016	0.00015	0.00014	0.00014
GA188	1.31123	0.00001	0.00001	0.00001	0.00001	0.00001
GA189	9.09594	0.00009	0.00007	0.00006	0.00006	0.00006
GA190	13.44807	0.00013	0.00010	0.00009	0.00009	0.00009
GA191	92.17472	0.00092	0.00068	0.00064	0.00063	0.00063
GA192	15.69296	0.00016	0.00012	0.00011	0.00011	0.00011
GA193	50.23534	0.00050	0.00037	0.00035	0.00034	0.00034
GA195	18.68395	0.00019	0.00014	0.00013	0.00013	0.00013
GA197	39.71591	0.00040	0.00029	0.00028	0.00027	0.00027
GA198	22.17172	0.00022	0.00016	0.00015	0.00015	0.00015
GA199	16.72635	0.00017	0.00012	0.00012	0.00011	0.00011
GA200	0.77347	0.00001	0.00001	0.00001	0.00001	0.00001
GA201	17.20338	0.00017	0.00013	0.00012	0.00012	0.00012
GA202	25.38118	0.00025	0.00019	0.00018	0.00017	0.00017
GA203	37.73218	0.00038	0.00028	0.00026	0.00026	0.00026
GA204	1.48505	0.00001	0.00001	0.00001	0.00001	0.00001
GA205	25.98113	0.00026	0.00019	0.00018	0.00018	0.00018
GA206	12.19642	0.00012	0.00009	0.00008	0.00008	0.00008
GA207	43.09744	0.00043	0.00032	0.00030	0.00030	0.00030
GA208	0.95098	0.00001	0.00001	0.00001	0.00001	0.00001
GA209	0.83974	0.00001	0.00001	0.00001	0.00001	0.00001
GA210	13.78761	0.00014	0.00010	0.00010	0.00009	0.00009
GA211	15.94112	0.00016	0.00012	0.00011	0.00011	0.00011
GA212	34.32725	0.00034	0.00025	0.00024	0.00024	0.00024
GA213	24.59430	0.00025	0.00018	0.00017	0.00017	0.00017
GA214	3.62331	0.00004	0.00003	0.00003	0.00002	0.00002
GA215	28.98914	0.00029	0.00021	0.00020	0.00020	0.00020
GA216	27.43698	0.00027	0.00020	0.00019	0.00019	0.00019
GA217	9.70556	0.00010	0.00007	0.00007	0.00007	0.00007
GA218	12.39142	0.00012	0.00009	0.00009	0.00009	0.00008
GA219	12.15703	0.00012	0.00009	0.00008	0.00008	0.00008
GA220	11.45000	0.00011	0.00008	0.00008	0.00008	0.00008
GA221	0.58072	0.00001	0.00000	0.00000	0.00000	0.00000
GA222	0.17258	0.00000	0.00000	0.00000	0.00000	0.00000
GA223	107.93808	0.00108	0.00080	0.00075	0.00074	0.00074
GA224	5.58077	0.00006	0.00004	0.00004	0.00004	0.00004
GA225	54.41343	0.00054	0.00040	0.00038	0.00037	0.00037
GA226	7.00929	0.00007	0.00005	0.00005	0.00005	0.00005

ID_Nó	∑ 0.5 Lij	E1=C0 ∑ 0.5 Lij	E2=E1.C1	E3=E2.C2	E4=E3.C3	E5=E4.C4
GA227	62.02408	0.00062	0.00046	0.00043	0.00043	0.00043
GA228	118.51480	0.00119	0.00088	0.00082	0.00081	0.00081
GA229	50.05574	0.00050	0.00037	0.00035	0.00034	0.00034
GA230	19.80004	0.00020	0.00015	0.00014	0.00014	0.00014
GA231	0.69751	0.00001	0.00001	0.00000	0.00000	0.00000
GA232	5.23500	0.00005	0.00004	0.00004	0.00004	0.00004
GA233	0.57160	0.00001	0.00000	0.00000	0.00000	0.00000
GA234	2.32686	0.00002	0.00002	0.00002	0.00002	0.00002
GA235	0.39565	0.00000	0.00000	0.00000	0.00000	0.00000
GA236	0.33877	0.00000	0.00000	0.00000	0.00000	0.00000
GA237	0.73500	0.00001	0.00001	0.00001	0.00001	0.00001
GA238	0.45000	0.00000	0.00000	0.00000	0.00000	0.00000
GA239	36.98765	0.00037	0.00027	0.00026	0.00025	0.00025
GA240	3.93697	0.00004	0.00003	0.00003	0.00003	0.00003
GA241	12.05889	0.00012	0.00009	0.00008	0.00008	0.00008
GA242	3.15517	0.00003	0.00002	0.00002	0.00002	0.00002
GA243	0.26732	0.00000	0.00000	0.00000	0.00000	0.00000
GA244	0.25502	0.00000	0.00000	0.00000	0.00000	0.00000
GA245	20.80819	0.00021	0.00015	0.00014	0.00014	0.00014
GA246	3.25870	0.00003	0.00002	0.00002	0.00002	0.00002
GA247	116.34095	0.00116	0.00086	0.00081	0.00080	0.00080
GA248	59.19222	0.00059	0.00044	0.00041	0.00041	0.00041
GA249	2.88638	0.00003	0.00002	0.00002	0.00002	0.00002
GA250	186.50667	0.00187	0.00138	0.00130	0.00128	0.00128
GA251	3.18500	0.00003	0.00002	0.00002	0.00002	0.00002
GA252	55.70659	0.00056	0.00041	0.00039	0.00038	0.00038
GA253	83.58968	0.00084	0.00062	0.00058	0.00057	0.00057
GA254	41.23268	0.00041	0.00030	0.00029	0.00028	0.00028
GA255	21.82732	0.00022	0.00016	0.00015	0.00015	0.00015
GA256	46.01074	0.00046	0.00034	0.00032	0.00032	0.00032
GA257	18.17987	0.00018	0.00013	0.00013	0.00012	0.00012
GA258	19.20479	0.00019	0.00014	0.00013	0.00013	0.00013
GA259	40.77794	0.00041	0.00030	0.00028	0.00028	0.00028
GA260	0.57966	0.00001	0.00000	0.00000	0.00000	0.00000
GA261	10.29053	0.00010	0.00008	0.00007	0.00007	0.00007
GA262	0.49570	0.00000	0.00000	0.00000	0.00000	0.00000
GA263	32.54626	0.00033	0.00024	0.00023	0.00022	0.00022
GA264	0.63611	0.00001	0.00000	0.00000	0.00000	0.00000
GA265	19.86186	0.00020	0.00015	0.00014	0.00014	0.00014
GA266	2.33784	0.00002	0.00002	0.00002	0.00002	0.00002
GA267	18.99859	0.00019	0.00014	0.00013	0.00013	0.00013
GA268	73.01291	0.00073	0.00054	0.00051	0.00050	0.00050
GA269	53.49688	0.00053	0.00040	0.00037	0.00037	0.00037
GA270	1.79657	0.00002	0.00001	0.00001	0.00001	0.00001
GA271	20.15000	0.00020	0.00015	0.00014	0.00014	0.00014
GA272	48.29214	0.00048	0.00036	0.00034	0.00033	0.00033
GA273	0.27555	0.00000	0.00000	0.00000	0.00000	0.00000
GA274	3.92967	0.00004	0.00003	0.00003	0.00003	0.00003
GA275	21.24895	0.00021	0.00016	0.00015	0.00015	0.00015
GA276	24.13899	0.00024	0.00018	0.00017	0.00017	0.00017
GA277	0.31717	0.00000	0.00000	0.00000	0.00000	0.00000
GA278	11.88051	0.00012	0.00009	0.00008	0.00008	0.00008
GA279	45.25313	0.00045	0.00033	0.00031	0.00031	0.00031
GA280	46.21326	0.00046	0.00034	0.00032	0.00032	0.00032
GA281	23.23115	0.00023	0.00017	0.00016	0.00016	0.00016
GA282	35.43312	0.00035	0.00026	0.00025	0.00024	0.00024

ID_Nó	∑ 0.5 Lij	E1=C0 ∑ 0.5 Lij	E2=E1.C1	E3=E2.C2	E4=E3.C3	E5=E4.C4
GA283	1.30386	0.00001	0.00001	0.00001	0.00001	0.00001
GA284	3.73943	0.00004	0.00003	0.00003	0.00003	0.00003
GA285	20.06236	0.00020	0.00015	0.00014	0.00014	0.00014
GA286	30.37873	0.00030	0.00022	0.00021	0.00021	0.00021
GA287	24.47618	0.00024	0.00018	0.00017	0.00017	0.00017
GA288	3.81718	0.00004	0.00003	0.00003	0.00003	0.00003
GA289	18.54046	0.00019	0.00014	0.00013	0.00013	0.00013
GA290	59.27439	0.00059	0.00044	0.00041	0.00041	0.00041
GA291	5.35332	0.00005	0.00004	0.00004	0.00004	0.00004
GA292	10.34266	0.00010	0.00008	0.00007	0.00007	0.00007
GA293	15.07773	0.00015	0.00011	0.00010	0.00010	0.00010
GA294	8.10953	0.00008	0.00006	0.00006	0.00006	0.00006
GA295	50.58173	0.00051	0.00037	0.00035	0.00035	0.00035
GA296	21.85928	0.00022	0.00016	0.00015	0.00015	0.00015
GA297	1.46912	0.00001	0.00001	0.00001	0.00001	0.00001
GA298	50.00320	0.00050	0.00037	0.00035	0.00034	0.00034
GA299	11.95135	0.00012	0.00009	0.00008	0.00008	0.00008
GA300	16.91342	0.00017	0.00013	0.00012	0.00012	0.00012
GA301	12.93799	0.00013	0.00010	0.00009	0.00009	0.00009
GA302	29.49321	0.00029	0.00022	0.00020	0.00020	0.00020
GA303	90.80229	0.00091	0.00067	0.00063	0.00062	0.00062
GA304	103.96535	0.00104	0.00077	0.00072	0.00071	0.00071
GA305	46.03228	0.00046	0.00034	0.00032	0.00032	0.00032
GA306	2.92688	0.00003	0.00002	0.00002	0.00002	0.00002
GA307	20.92750	0.00021	0.00015	0.00015	0.00014	0.00014
GA308	0.30073	0.00000	0.00000	0.00000	0.00000	0.00000
GA309	3.77548	0.00004	0.00003	0.00003	0.00003	0.00003
GA310	24.69399	0.00025	0.00018	0.00017	0.00017	0.00017
GA311	56.92849	0.00057	0.00042	0.00040	0.00039	0.00039
GA312	83.80482	0.00084	0.00062	0.00058	0.00058	0.00057
GA313	42.45805	0.00042	0.00031	0.00029	0.00029	0.00029
GA314	26.20832	0.00026	0.00019	0.00018	0.00018	0.00018
GA315	18.95044	0.00019	0.00014	0.00013	0.00013	0.00013
GA316	98.92267	0.00099	0.00073	0.00069	0.00068	0.00068
GA317	49.21517	0.00049	0.00036	0.00034	0.00034	0.00034
GA318	0.18855	0.00000	0.00000	0.00000	0.00000	0.00000
GA319	0.23337	0.00000	0.00000	0.00000	0.00000	0.00000
GA320	4.50935	0.00005	0.00003	0.00003	0.00003	0.00003
GA321	1.02273	0.00001	0.00001	0.00001	0.00001	0.00001
GA322	0.18920	0.00000	0.00000	0.00000	0.00000	0.00000
GA323	0.13052	0.00000	0.00000	0.00000	0.00000	0.00000
GA324	15.68975	0.00016	0.00012	0.00011	0.00011	0.00011
GA325	14.97872	0.00015	0.00011	0.00010	0.00010	0.00010
GA326	7.25784	0.00007	0.00005	0.00005	0.00005	0.00005
GA327	6.82537	0.00007	0.00005	0.00005	0.00005	0.00005
GA328	18.82669	0.00019	0.00014	0.00013	0.00013	0.00013
GA329	19.04955	0.00019	0.00014	0.00013	0.00013	0.00013
GA330	0.80717	0.00001	0.00001	0.00001	0.00001	0.00001
GA331	20.43592	0.00020	0.00015	0.00014	0.00014	0.00014
GA332	28.16318	0.00028	0.00021	0.00020	0.00019	0.00019
GA333	35.24995	0.00035	0.00026	0.00024	0.00024	0.00024
GA334	107.09383	0.00107	0.00079	0.00074	0.00073	0.00073
GA335	10.47277	0.00010	0.00008	0.00007	0.00007	0.00007
GA336	29.28427	0.00029	0.00022	0.00020	0.00020	0.00020
GA337	19.06059	0.00019	0.00014	0.00013	0.00013	0.00013
GA338	3.41500	0.00003	0.00003	0.00002	0.00002	0.00002

ID_Nó	∑ 0.5 Lij	E1=C0 ∑ 0.5 Lij	E2=E1.C1	E3=E2.C2	E4=E3.C3	E5=E4.C4
GA339	2.27201	0.00002	0.00002	0.00002	0.00002	0.00002
GA340	28.49831	0.00028	0.00021	0.00020	0.00020	0.00020
GA341	2.77130	0.00003	0.00002	0.00002	0.00002	0.00002
GA342	6.34892	0.00006	0.00005	0.00004	0.00004	0.00004
GA343	63.04901	0.00063	0.00047	0.00044	0.00043	0.00043
GA344	1.57472	0.00002	0.00001	0.00001	0.00001	0.00001
GA345	30.93299	0.00031	0.00023	0.00021	0.00021	0.00021
GA346	68.24175	0.00068	0.00050	0.00047	0.00047	0.00047
GA347	0.56868	0.00001	0.00000	0.00000	0.00000	0.00000
GA348	94.50140	0.00095	0.00070	0.00066	0.00065	0.00065
GA349	3.11786	0.00003	0.00002	0.00002	0.00002	0.00002
GA350	3.10092	0.00003	0.00002	0.00002	0.00002	0.00002
GA351	25.92682	0.00026	0.00019	0.00018	0.00018	0.00018
GA352	30.91312	0.00031	0.00023	0.00021	0.00021	0.00021
GA353	51.27675	0.00051	0.00038	0.00036	0.00035	0.00035
GA354	23.13517	0.00023	0.00017	0.00016	0.00016	0.00016
GA355	0.19444	0.00000	0.00000	0.00000	0.00000	0.00000
GA356	1.31108	0.00001	0.00001	0.00001	0.00001	0.00001
GA357	8.23232	0.00008	0.00006	0.00006	0.00006	0.00006
GA358	2.86759	0.00003	0.00002	0.00002	0.00002	0.00002
GA359	52.70042	0.00053	0.00039	0.00037	0.00036	0.00036
GA360	47.51879	0.00048	0.00035	0.00033	0.00033	0.00033
GA361	52.18733	0.00052	0.00039	0.00036	0.00036	0.00036
GA362	22.58979	0.00023	0.00017	0.00016	0.00016	0.00015
GA363	29.36695	0.00029	0.00022	0.00020	0.00020	0.00020
GA364	7.81507	0.00008	0.00006	0.00005	0.00005	0.00005
GA365	1.93162	0.00002	0.00001	0.00001	0.00001	0.00001
GA366	37.70732	0.00038	0.00028	0.00026	0.00026	0.00026
GA367	29.44096	0.00029	0.00022	0.00020	0.00020	0.00020
GA368	24.48465	0.00024	0.00018	0.00017	0.00017	0.00017
GA369	20.19056	0.00020	0.00015	0.00014	0.00014	0.00014
GA370	25.28787	0.00025	0.00019	0.00018	0.00017	0.00017
GA371	113.63657	0.00114	0.00084	0.00079	0.00078	0.00078
GA372	88.18552	0.00088	0.00065	0.00061	0.00061	0.00060
GA373	3.90257	0.00004	0.00003	0.00003	0.00003	0.00003
GA374	50.51252	0.00051	0.00037	0.00035	0.00035	0.00035
GA375	12.32886	0.00012	0.00009	0.00009	0.00008	0.00008
GA376	1.67893	0.00002	0.00001	0.00001	0.00001	0.00001
GA377	14.71876	0.00015	0.00011	0.00010	0.00010	0.00010
GA378	27.97333	0.00028	0.00021	0.00019	0.00019	0.00019
GA379	13.69792	0.00014	0.00010	0.00010	0.00009	0.00009
GA380	52.37244	0.00052	0.00039	0.00036	0.00036	0.00036
GA381	10.65085	0.00011	0.00008	0.00007	0.00007	0.00007
GA382	14.58151	0.00015	0.00011	0.00010	0.00010	0.00010
GA383	40.32913	0.00040	0.00030	0.00028	0.00028	0.00028
GA384	8.28142	0.00008	0.00006	0.00006	0.00006	0.00006
GA385	59.12590	0.00059	0.00044	0.00041	0.00041	0.00041
GA386	98.10110	0.00098	0.00073	0.00068	0.00067	0.00067
GA387	4.11007	0.00004	0.00003	0.00003	0.00003	0.00003
GA388	0.63845	0.00001	0.00000	0.00000	0.00000	0.00000
GA389	32.55161	0.00033	0.00024	0.00023	0.00022	0.00022
GA390	59.27162	0.00059	0.00044	0.00041	0.00041	0.00041
GA391	1.17002	0.00001	0.00001	0.00001	0.00001	0.00001
GA392	27.80385	0.00028	0.00021	0.00019	0.00019	0.00019
GA393	21.88417	0.00022	0.00016	0.00015	0.00015	0.00015
GA394	5.32737	0.00005	0.00004	0.00004	0.00004	0.00004

ID_Nó	∑ 0.5 Lij	E1=C0 ∑ 0.5 Lij	E2=E1.C1	E3=E2.C2	E4=E3.C3	E5=E4.C4
GA395	0.26442	0.00000	0.00000	0.00000	0.00000	0.00000
GA396	113.72102	0.00114	0.00084	0.00079	0.00078	0.00078
GA397	0.89718	0.00001	0.00001	0.00001	0.00001	0.00001
GA398	131.10000	0.00131	0.00097	0.00091	0.00090	0.00090
GA399	48.43542	0.00048	0.00036	0.00034	0.00033	0.00033
GA400	33.06693	0.00033	0.00024	0.00023	0.00023	0.00023
GA401	15.92161	0.00016	0.00012	0.00011	0.00011	0.00011
GA402	6.97231	0.00007	0.00005	0.00005	0.00005	0.00005
GA403	6.87990	0.00007	0.00005	0.00005	0.00005	0.00005
GA404	0.14431	0.00000	0.00000	0.00000	0.00000	0.00000
GA405	67.29500	0.00067	0.00050	0.00047	0.00046	0.00046
GA406	0.12684	0.00000	0.00000	0.00000	0.00000	0.00000
GA407	1.87463	0.00002	0.00001	0.00001	0.00001	0.00001
GA408	0.36527	0.00000	0.00000	0.00000	0.00000	0.00000
GA409	24.98509	0.00025	0.00018	0.00017	0.00017	0.00017
GA410	10.84244	0.00011	0.00008	0.00008	0.00007	0.00007
GA411	30.71684	0.00031	0.00023	0.00021	0.00021	0.00021
GA412	46.38521	0.00046	0.00034	0.00032	0.00032	0.00032
GA413	6.95291	0.00007	0.00005	0.00005	0.00005	0.00005
GA414	7.50580	0.00008	0.00006	0.00005	0.00005	0.00005
GA415	14.29262	0.00014	0.00011	0.00010	0.00010	0.00010
GA416	15.32918	0.00015	0.00011	0.00011	0.00011	0.00011
GA417	59.98409	0.00060	0.00044	0.00042	0.00041	0.00041
GA418	7.97984	0.00008	0.00006	0.00006	0.00005	0.00005
GA419	0.70466	0.00001	0.00001	0.00000	0.00000	0.00000
GA420	2.10765	0.00002	0.00002	0.00001	0.00001	0.00001
GA421	7.41088	0.00007	0.00005	0.00005	0.00005	0.00005
GA422	40.54144	0.00041	0.00030	0.00028	0.00028	0.00028
GA423	0.65424	0.00001	0.00000	0.00000	0.00000	0.00000
GA424	5.34427	0.00005	0.00004	0.00004	0.00004	0.00004
GA425	32.64227	0.00033	0.00024	0.00023	0.00022	0.00022
GA426	13.40437	0.00013	0.00010	0.00009	0.00009	0.00009
GA427	2.44812	0.00002	0.00002	0.00002	0.00002	0.00002
GA428	21.86024	0.00022	0.00016	0.00015	0.00015	0.00015
GA429	0.16077	0.00000	0.00000	0.00000	0.00000	0.00000
GA430	37.78585	0.00038	0.00028	0.00026	0.00026	0.00026
GA431	27.16117	0.00027	0.00020	0.00019	0.00019	0.00019
GA432	38.45021	0.00038	0.00028	0.00027	0.00026	0.00026
GA433	1.18500	0.00001	0.00001	0.00001	0.00001	0.00001
GA434	0.36000	0.00000	0.00000	0.00000	0.00000	0.00000
GA435	0.64818	0.00001	0.00000	0.00000	0.00000	0.00000
GA436	1.72902	0.00002	0.00001	0.00001	0.00001	0.00001
GA437	30.40220	0.00030	0.00022	0.00021	0.00021	0.00021
GA438	15.67441	0.00016	0.00012	0.00011	0.00011	0.00011
GA439	2.47923	0.00002	0.00002	0.00002	0.00002	0.00002
GA440	14.32042	0.00014	0.00011	0.00010	0.00010	0.00010
GA441	19.64329	0.00020	0.00015	0.00014	0.00013	0.00013
GA442	17.04923	0.00017	0.00013	0.00012	0.00012	0.00012
GA443	18.77941	0.00019	0.00014	0.00013	0.00013	0.00013
GA444	22.67979	0.00023	0.00017	0.00016	0.00016	0.00016
GA445	8.71844	0.00009	0.00006	0.00006	0.00006	0.00006
GA446	7.20481	0.00007	0.00005	0.00005	0.00005	0.00005
GA447	0.47082	0.00000	0.00000	0.00000	0.00000	0.00000
GA448	8.71802	0.00009	0.00006	0.00006	0.00006	0.00006
GA449	13.02260	0.00013	0.00010	0.00009	0.00009	0.00009
GA450	5.71693	0.00006	0.00004	0.00004	0.00004	0.00004

ID_Nó	∑ 0.5 Lij	E1=C0 ∑ 0.5 Lij	E2=E1.C1	E3=E2.C2	E4=E3.C3	E5=E4.C4
GA451	0.89263	0.00001	0.00001	0.00001	0.00001	0.00001
GA452	47.50256	0.00048	0.00035	0.00033	0.00033	0.00033
GA453	1.18119	0.00001	0.00001	0.00001	0.00001	0.00001
GA454	198.66629	0.00199	0.00147	0.00138	0.00136	0.00136
GA455	10.36398	0.00010	0.00008	0.00007	0.00007	0.00007
GA456	10.94040	0.00011	0.00008	0.00008	0.00008	0.00007
GA457	6.42585	0.00006	0.00005	0.00004	0.00004	0.00004
GA458	25.34641	0.00025	0.00019	0.00018	0.00017	0.00017
GA460	12.24413	0.00012	0.00009	0.00009	0.00008	0.00008
GA461	18.66151	0.00019	0.00014	0.00013	0.00013	0.00013
GA462	15.62561	0.00016	0.00012	0.00011	0.00011	0.00011
GA463	17.47797	0.00017	0.00013	0.00012	0.00012	0.00012
GA464	13.31411	0.00013	0.00010	0.00009	0.00009	0.00009
GA465	13.53109	0.00014	0.00010	0.00009	0.00009	0.00009
GA466	60.53421	0.00061	0.00045	0.00042	0.00042	0.00041
GA467	88.26329	0.00088	0.00065	0.00061	0.00061	0.00060
GA468	53.46561	0.00053	0.00040	0.00037	0.00037	0.00037
GA469	32.06264	0.00032	0.00024	0.00022	0.00022	0.00022
GA470	10.43798	0.00010	0.00008	0.00007	0.00007	0.00007
GA471	10.17626	0.00010	0.00008	0.00007	0.00007	0.00007
GA472	42.18238	0.00042	0.00031	0.00029	0.00029	0.00029
GA473	77.71496	0.00078	0.00057	0.00054	0.00053	0.00053
GA474	41.67446	0.00042	0.00031	0.00029	0.00029	0.00029
GA475	67.59998	0.00068	0.00050	0.00047	0.00046	0.00046
GA476	2.33482	0.00002	0.00002	0.00002	0.00002	0.00002
GA477	5.58008	0.00006	0.00004	0.00004	0.00004	0.00004
GA478	2.47297	0.00002	0.00002	0.00002	0.00002	0.00002
GA479	0.34368	0.00000	0.00000	0.00000	0.00000	0.00000
GA480	0.87621	0.00001	0.00001	0.00001	0.00001	0.00001
GA481	20.20346	0.00020	0.00015	0.00014	0.00014	0.00014
GA482	1.17182	0.00001	0.00001	0.00001	0.00001	0.00001
GA483	77.69482	0.00078	0.00057	0.00054	0.00053	0.00053
GA484	34.91279	0.00035	0.00026	0.00024	0.00024	0.00024
GA485	20.04370	0.00020	0.00015	0.00014	0.00014	0.00014
GA486	8.72435	0.00009	0.00006	0.00006	0.00006	0.00006
GA487	0.87385	0.00001	0.00001	0.00001	0.00001	0.00001
GA488	21.15186	0.00021	0.00016	0.00015	0.00015	0.00014
GA489	2.36592	0.00002	0.00002	0.00002	0.00002	0.00002
GA490	30.00666	0.00030	0.00022	0.00021	0.00021	0.00021
GA491	28.94747	0.00029	0.00021	0.00020	0.00020	0.00020
GA492	2.26205	0.00002	0.00002	0.00002	0.00002	0.00002
GA493	16.40180	0.00016	0.00012	0.00011	0.00011	0.00011
GA494	2.24639	0.00002	0.00002	0.00002	0.00002	0.00002
GA495	28.45545	0.00028	0.00021	0.00020	0.00020	0.00020
GA496	16.89195	0.00017	0.00012	0.00012	0.00012	0.00012
GA497	20.19982	0.00020	0.00015	0.00014	0.00014	0.00014
GA498	15.91270	0.00016	0.00012	0.00011	0.00011	0.00011
GA499	12.52971	0.00013	0.00009	0.00009	0.00009	0.00009
GA500	68.37418	0.00068	0.00051	0.00047	0.00047	0.00047
GA501	16.81596	0.00017	0.00012	0.00012	0.00012	0.00012
GA502	116.24602	0.00116	0.00086	0.00081	0.00080	0.00080
GA503	1.31507	0.00001	0.00001	0.00001	0.00001	0.00001
GA504	44.85983	0.00045	0.00033	0.00031	0.00031	0.00031
GA505	4.32597	0.00004	0.00003	0.00003	0.00003	0.00003
GA506	31.95259	0.00032	0.00024	0.00022	0.00022	0.00022
GA507	71.23376	0.00071	0.00053	0.00049	0.00049	0.00049

ID_Nó	∑ 0.5 Lij	E1=C0 ∑ 0.5 Lij	E2=E1.C1	E3=E2.C2	E4=E3.C3	E5=E4.C4
GA508	0.77928	0.00001	0.00001	0.00001	0.00001	0.00001
GA509	4.98638	0.00005	0.00004	0.00003	0.00003	0.00003
GA510	86.91688	0.00087	0.00064	0.00060	0.00060	0.00060
GA511	0.52601	0.00001	0.00000	0.00000	0.00000	0.00000
GA512	97.15803	0.00097	0.00072	0.00067	0.00067	0.00067
GA513	0.26829	0.00000	0.00000	0.00000	0.00000	0.00000
GA514	2.53244	0.00003	0.00002	0.00002	0.00002	0.00002
GA515	2.34691	0.00002	0.00002	0.00002	0.00002	0.00002
GA516	1.09339	0.00001	0.00001	0.00001	0.00001	0.00001
GA517	1.68492	0.00002	0.00001	0.00001	0.00001	0.00001
GA518	23.32705	0.00023	0.00017	0.00016	0.00016	0.00016
GA519	9.98993	0.00010	0.00007	0.00007	0.00007	0.00007
GA520	4.33362	0.00004	0.00003	0.00003	0.00003	0.00003
GA521	40.51724	0.00041	0.00030	0.00028	0.00028	0.00028
GA522	11.72639	0.00012	0.00009	0.00008	0.00008	0.00008
GA523	83.75772	0.00084	0.00062	0.00058	0.00058	0.00057
GA525	17.34599	0.00017	0.00013	0.00012	0.00012	0.00012
GA526	20.67294	0.00021	0.00015	0.00014	0.00014	0.00014
GA527	3.15570	0.00003	0.00002	0.00002	0.00002	0.00002
GA528	0.43100	0.00000	0.00000	0.00000	0.00000	0.00000
GA529	6.14735	0.00006	0.00005	0.00004	0.00004	0.00004
GA530	16.73216	0.00017	0.00012	0.00012	0.00011	0.00011
GA531	59.07351	0.00059	0.00044	0.00041	0.00041	0.00040
GA532	31.03781	0.00031	0.00023	0.00022	0.00021	0.00021
GA533	11.48399	0.00011	0.00008	0.00008	0.00008	0.00008
GA534	51.97886	0.00052	0.00038	0.00036	0.00036	0.00036
GA535	18.93425	0.00019	0.00014	0.00013	0.00013	0.00013
GA536	6.77536	0.00007	0.00005	0.00005	0.00005	0.00005
GA537	126.37054	0.00126	0.00093	0.00088	0.00087	0.00087
GA538	12.30152	0.00012	0.00009	0.00009	0.00008	0.00008
GA539	0.94763	0.00001	0.00001	0.00001	0.00001	0.00001
GA540	69.44981	0.00069	0.00051	0.00048	0.00048	0.00048
GA541	20.17312	0.00020	0.00015	0.00014	0.00014	0.00014
GA542	23.75413	0.00024	0.00018	0.00016	0.00016	0.00016
GA543	56.14885	0.00056	0.00042	0.00039	0.00039	0.00038
GA544	23.20821	0.00023	0.00017	0.00016	0.00016	0.00016
GA545	45.15576	0.00045	0.00033	0.00031	0.00031	0.00031
GA546	39.53507	0.00040	0.00029	0.00027	0.00027	0.00027
GA547	0.78500	0.00001	0.00001	0.00001	0.00001	0.00001
GA548	15.58924	0.00016	0.00012	0.00011	0.00011	0.00011
GA549	22.10893	0.00022	0.00016	0.00015	0.00015	0.00015
GA550	17.10730	0.00017	0.00013	0.00012	0.00012	0.00012
GA551	3.10924	0.00003	0.00002	0.00002	0.00002	0.00002
GA552	91.74686	0.00092	0.00068	0.00064	0.00063	0.00063
GA553	47.88290	0.00048	0.00035	0.00033	0.00033	0.00033
GA554	37.61066	0.00038	0.00028	0.00026	0.00026	0.00026
GA555	17.40230	0.00017	0.00013	0.00012	0.00012	0.00012
GA556	63.49989	0.00063	0.00047	0.00044	0.00044	0.00044
GA557	3.20883	0.00003	0.00002	0.00002	0.00002	0.00002
GA558	64.87187	0.00065	0.00048	0.00045	0.00045	0.00044
GA559	9.62122	0.00010	0.00007	0.00007	0.00007	0.00007
GA560	61.53267	0.00062	0.00045	0.00043	0.00042	0.00042
GA561	9.62122	0.00010	0.00007	0.00007	0.00007	0.00007
GA562	7.01175	0.00007	0.00005	0.00005	0.00005	0.00005
GA563	6.28032	0.00006	0.00005	0.00004	0.00004	0.00004
GA564	21.61377	0.00022	0.00016	0.00015	0.00015	0.00015

ID_Nó	∑ 0.5 Lij	E1=C0 ∑ 0.5 Lij	E2=E1.C1	E3=E2.C2	E4=E3.C3	E5=E4.C4
GA565	4.32476	0.00004	0.00003	0.00003	0.00003	0.00003
GA566	82.17574	0.00082	0.00061	0.00057	0.00056	0.00056
GA567	0.46984	0.00000	0.00000	0.00000	0.00000	0.00000
GA568	0.26744	0.00000	0.00000	0.00000	0.00000	0.00000
GA569	5.34989	0.00005	0.00004	0.00004	0.00004	0.00004
GA570	35.52448	0.00036	0.00026	0.00025	0.00024	0.00024
GA571	6.59854	0.00007	0.00005	0.00005	0.00005	0.00005
GA572	25.25141	0.00025	0.00019	0.00018	0.00017	0.00017
GA573	5.37638	0.00005	0.00004	0.00004	0.00004	0.00004
GA574	2.33989	0.00002	0.00002	0.00002	0.00002	0.00002
GA575	81.84173	0.00082	0.00061	0.00057	0.00056	0.00056
GA576	16.31345	0.00016	0.00012	0.00011	0.00011	0.00011
GA577	50.71052	0.00051	0.00037	0.00035	0.00035	0.00035
GA578	6.42127	0.00006	0.00005	0.00004	0.00004	0.00004
GA579	2.10751	0.00002	0.00002	0.00001	0.00001	0.00001
GA580	96.78268	0.00097	0.00072	0.00067	0.00066	0.00066
GA581	19.67701	0.00020	0.00015	0.00014	0.00014	0.00013
GA582	20.29903	0.00020	0.00015	0.00014	0.00014	0.00014
GA583	10.34299	0.00010	0.00008	0.00007	0.00007	0.00007
GA584	33.56279	0.00034	0.00025	0.00023	0.00023	0.00023
GA585	2.97335	0.00003	0.00002	0.00002	0.00002	0.00002
GA586	25.65406	0.00026	0.00019	0.00018	0.00018	0.00018
GA587	3.64407	0.00004	0.00003	0.00003	0.00003	0.00002
GA588	22.42789	0.00022	0.00017	0.00016	0.00015	0.00015
GA589	2.63534	0.00003	0.00002	0.00002	0.00002	0.00002
GA590	3.68123	0.00004	0.00003	0.00003	0.00003	0.00003
GA591	11.90497	0.00012	0.00009	0.00008	0.00008	0.00008
GA592	28.86667	0.00029	0.00021	0.00020	0.00020	0.00020
GA593	44.81580	0.00045	0.00033	0.00031	0.00031	0.00031
GA594	14.11834	0.00014	0.00010	0.00010	0.00010	0.00010
GA595	53.64777	0.00054	0.00040	0.00037	0.00037	0.00037
GA596	8.06418	0.00008	0.00006	0.00006	0.00006	0.00006
GA597	34.42243	0.00034	0.00025	0.00024	0.00024	0.00024
GA598	0.93394	0.00001	0.00001	0.00001	0.00001	0.00001
GA599	11.61095	0.00012	0.00009	0.00008	0.00008	0.00008
GA600	1.04202	0.00001	0.00001	0.00001	0.00001	0.00001
GA601	42.55662	0.00043	0.00031	0.00030	0.00029	0.00029
GA602	32.95457	0.00033	0.00024	0.00023	0.00023	0.00023
GA603	50.20662	0.00050	0.00037	0.00035	0.00034	0.00034
GA604	54.00229	0.00054	0.00040	0.00038	0.00037	0.00037
GA605	10.62522	0.00011	0.00008	0.00007	0.00007	0.00007
GA606	28.38710	0.00028	0.00021	0.00020	0.00019	0.00019
GA607	22.64980	0.00023	0.00017	0.00016	0.00016	0.00016
GA608	0.25331	0.00000	0.00000	0.00000	0.00000	0.00000
GA609	1.10653	0.00001	0.00001	0.00001	0.00001	0.00001
GA610	32.89577	0.00033	0.00024	0.00023	0.00023	0.00023
GA611	44.58456	0.00045	0.00033	0.00031	0.00031	0.00031
GA612	8.24920	0.00008	0.00006	0.00006	0.00006	0.00006
GA613	4.08525	0.00004	0.00003	0.00003	0.00003	0.00003
GA614	21.35435	0.00021	0.00016	0.00015	0.00015	0.00015
GA615	1.11855	0.00001	0.00001	0.00001	0.00001	0.00001
GA616	4.12842	0.00004	0.00003	0.00003	0.00003	0.00003
GA617	5.12153	0.00005	0.00004	0.00004	0.00004	0.00004
GA619	95.34031	0.00095	0.00070	0.00066	0.00065	0.00065
GA620	21.13840	0.00021	0.00016	0.00015	0.00015	0.00014
GA621	29.87581	0.00030	0.00022	0.00021	0.00021	0.00020

ID_Nó	∑ 0.5 Lij	E1=C0 ∑ 0.5 Lij	E2=E1.C1	E3=E2.C2	E4=E3.C3	E5=E4.C4
GA622	21.37324	0.00021	0.00016	0.00015	0.00015	0.00015
GA623	0.40573	0.00000	0.00000	0.00000	0.00000	0.00000
GA624	23.84120	0.00024	0.00018	0.00017	0.00016	0.00016
GA625	1.08740	0.00001	0.00001	0.00001	0.00001	0.00001
GA626	31.97761	0.00032	0.00024	0.00022	0.00022	0.00022
GA627	24.23982	0.00024	0.00018	0.00017	0.00017	0.00017
GA628	23.14298	0.00023	0.00017	0.00016	0.00016	0.00016
GA629	39.03835	0.00039	0.00029	0.00027	0.00027	0.00027
GA630	38.22018	0.00038	0.00028	0.00027	0.00026	0.00026
GA631	29.23185	0.00029	0.00022	0.00020	0.00020	0.00020
GA632	22.39791	0.00022	0.00017	0.00016	0.00015	0.00015
GA633	16.85436	0.00017	0.00012	0.00012	0.00012	0.00012
GA634	0.20004	0.00000	0.00000	0.00000	0.00000	0.00000
GA635	67.02428	0.00067	0.00050	0.00047	0.00046	0.00046
GA636	2.97613	0.00003	0.00002	0.00002	0.00002	0.00002
GA637	20.78500	0.00021	0.00015	0.00014	0.00014	0.00014
GA638	17.87599	0.00018	0.00013	0.00012	0.00012	0.00012
GA639	59.08690	0.00059	0.00044	0.00041	0.00041	0.00041
GA640	34.10608	0.00034	0.00025	0.00024	0.00023	0.00023
GA641	6.14425	0.00006	0.00005	0.00004	0.00004	0.00004
GA642	0.64568	0.00001	0.00000	0.00000	0.00000	0.00000
GA643	45.66695	0.00046	0.00034	0.00032	0.00031	0.00031
GA644	6.32486	0.00006	0.00005	0.00004	0.00004	0.00004
GA645	14.57545	0.00015	0.00011	0.00010	0.00010	0.00010
GA646	19.50079	0.00020	0.00014	0.00014	0.00013	0.00013
GA647	19.33814	0.00019	0.00014	0.00013	0.00013	0.00013
GA648	96.86831	0.00097	0.00072	0.00067	0.00067	0.00066
GA649	16.71732	0.00017	0.00012	0.00012	0.00011	0.00011
GA650	34.26296	0.00034	0.00025	0.00024	0.00024	0.00023
GA651	10.63206	0.00011	0.00008	0.00007	0.00007	0.00007
GA652	1.30645	0.00001	0.00001	0.00001	0.00001	0.00001
GA653	11.72372	0.00012	0.00009	0.00008	0.00008	0.00008
GA654	1.39306	0.00001	0.00001	0.00001	0.00001	0.00001
GA655	24.84601	0.00025	0.00018	0.00017	0.00017	0.00017
GA656	24.11238	0.00024	0.00018	0.00017	0.00017	0.00017
GA657	24.86737	0.00025	0.00018	0.00017	0.00017	0.00017
GA658	29.09710	0.00029	0.00022	0.00020	0.00020	0.00020
GA659	5.72255	0.00006	0.00004	0.00004	0.00004	0.00004
GA660	12.55078	0.00013	0.00009	0.00009	0.00009	0.00009
GA661	2.06311	0.00002	0.00002	0.00001	0.00001	0.00001
GA662	10.91959	0.00011	0.00008	0.00008	0.00007	0.00007
GA663	13.25616	0.00013	0.00010	0.00009	0.00009	0.00009
GA664	5.52422	0.00006	0.00004	0.00004	0.00004	0.00004
GA665	57.72997	0.00058	0.00043	0.00040	0.00040	0.00040
GA666	0.45809	0.00000	0.00000	0.00000	0.00000	0.00000
GA667	0.00965	0.00000	0.00000	0.00000	0.00000	0.00000
GA668	71.66926	0.00072	0.00053	0.00050	0.00049	0.00049
GA669	0.48868	0.00000	0.00000	0.00000	0.00000	0.00000
GA670	132.31315	0.00132	0.00098	0.00092	0.00091	0.00091
GA671	23.12254	0.00023	0.00017	0.00016	0.00016	0.00016
GA672	11.38575	0.00011	0.00008	0.00008	0.00008	0.00008
GA673	20.62643	0.00021	0.00015	0.00014	0.00014	0.00014
GA674	19.27174	0.00019	0.00014	0.00013	0.00013	0.00013
GA675	42.02427	0.00042	0.00031	0.00029	0.00029	0.00029
GA676	20.70821	0.00021	0.00015	0.00014	0.00014	0.00014
GA677	70.38012	0.00070	0.00052	0.00049	0.00048	0.00048

ID_Nó	∑ 0.5 Lij	E1=C0 ∑ 0.5 Lij	E2=E1.C1	E3=E2.C2	E4=E3.C3	E5=E4.C4
GA678	6.41640	0.00006	0.00005	0.00004	0.00004	0.00004
GA679	60.02278	0.00060	0.00044	0.00042	0.00041	0.00041
GA681	25.67174	0.00026	0.00019	0.00018	0.00018	0.00018
GA682	21.90482	0.00022	0.00016	0.00015	0.00015	0.00015
GA683	5.13366	0.00005	0.00004	0.00004	0.00004	0.00004
GA684	34.79242	0.00035	0.00026	0.00024	0.00024	0.00024
GA685	2.37438	0.00002	0.00002	0.00002	0.00002	0.00002
GA686	14.37438	0.00014	0.00011	0.00010	0.00010	0.00010
GA688	203.40802	0.00203	0.00150	0.00141	0.00140	0.00139
GA689	36.27619	0.00036	0.00027	0.00025	0.00025	0.00025
GA690	21.10651	0.00021	0.00016	0.00015	0.00014	0.00014
GA691	16.31848	0.00016	0.00012	0.00011	0.00011	0.00011
GA692	143.69398	0.00144	0.00106	0.00100	0.00099	0.00098
GA693	22.40612	0.00022	0.00017	0.00016	0.00015	0.00015
GA694	30.39416	0.00030	0.00022	0.00021	0.00021	0.00021
GA695	1.35281	0.00001	0.00001	0.00001	0.00001	0.00001
GA696	28.48569	0.00028	0.00021	0.00020	0.00020	0.00020
GA697	97.80578	0.00098	0.00072	0.00068	0.00067	0.00067
GA699	31.02911	0.00031	0.00023	0.00022	0.00021	0.00021
GA700	47.32007	0.00047	0.00035	0.00033	0.00032	0.00032
GA701	111.49922	0.00111	0.00082	0.00077	0.00077	0.00076
GA702	4.98019	0.00005	0.00004	0.00003	0.00003	0.00003
GA703	15.49797	0.00015	0.00011	0.00011	0.00011	0.00011
GA704	14.86274	0.00015	0.00011	0.00010	0.00010	0.00010
GA705	35.92433	0.00036	0.00027	0.00025	0.00025	0.00025
GA706	67.57261	0.00068	0.00050	0.00047	0.00046	0.00046
GA707	15.59516	0.00016	0.00012	0.00011	0.00011	0.00011
GA708	2.15127	0.00002	0.00002	0.00001	0.00001	0.00001
GA709	13.34355	0.00013	0.00010	0.00009	0.00009	0.00009
GA710	191.81405	0.00192	0.00142	0.00133	0.00132	0.00131
GA711	51.23921	0.00051	0.00038	0.00036	0.00035	0.00035
GA712	8.23376	0.00008	0.00006	0.00006	0.00006	0.00006
GA713	7.75993	0.00008	0.00006	0.00005	0.00005	0.00005
GA714	24.99863	0.00025	0.00018	0.00017	0.00017	0.00017
GA715	48.25914	0.00048	0.00036	0.00034	0.00033	0.00033
GA716	0.22401	0.00000	0.00000	0.00000	0.00000	0.00000
GA717	3.58595	0.00004	0.00003	0.00002	0.00002	0.00002
GA718	0.22244	0.00000	0.00000	0.00000	0.00000	0.00000
GA719	86.86538	0.00087	0.00064	0.00060	0.00060	0.00060
GA720	0.41562	0.00000	0.00000	0.00000	0.00000	0.00000
GA721	3.63681	0.00004	0.00003	0.00003	0.00002	0.00002
GA722	0.02362	0.00000	0.00000	0.00000	0.00000	0.00000
GA723	12.20626	0.00012	0.00009	0.00008	0.00008	0.00008
GA724	110.67095	0.00111	0.00082	0.00077	0.00076	0.00076
GA725	3.82091	0.00004	0.00003	0.00003	0.00003	0.00003
GA726	3.60000	0.00004	0.00003	0.00003	0.00002	0.00002
GA730	41.98912	0.00042	0.00031	0.00029	0.00029	0.00029
GA731	7.56900	0.00008	0.00006	0.00005	0.00005	0.00005
GA732	23.58218	0.00024	0.00017	0.00016	0.00016	0.00016
GA733	187.48503	0.00187	0.00139	0.00130	0.00129	0.00129
GA734	18.57144	0.00019	0.00014	0.00013	0.00013	0.00013
GA735	0.65648	0.00001	0.00000	0.00000	0.00000	0.00000
GA736	0.14818	0.00000	0.00000	0.00000	0.00000	0.00000
GA737	4.33513	0.00004	0.00003	0.00003	0.00003	0.00003
GA738	45.05643	0.00045	0.00033	0.00031	0.00031	0.00031
GA739	68.10974	0.00068	0.00050	0.00047	0.00047	0.00047

ID_Nó	∑ 0.5 Lij	E1=C0 ∑ 0.5 Lij	E2=E1.C1	E3=E2.C2	E4=E3.C3	E5=E4.C4
GA740	8.08064	0.00008	0.00006	0.00006	0.00006	0.00006
GA741	9.33649	0.00009	0.00007	0.00006	0.00006	0.00006
GA742	142.26360	0.00142	0.00105	0.00099	0.00098	0.00098
GA743	31.17103	0.00031	0.00023	0.00022	0.00021	0.00021
GA744	4.45500	0.00004	0.00003	0.00003	0.00003	0.00003
GA745	1.56307	0.00002	0.00001	0.00001	0.00001	0.00001
GA746	15.23000	0.00015	0.00011	0.00011	0.00010	0.00010
Res_Gaula	2.92000	0.00003	0.00002	0.00002	0.00002	0.00002

Appendix II – Portuguese Municipalities Energy Consumptions and Entering Water

It was considered only the WDS values of the municipalities with both valid data (Energy Consumption and Entering water in the systems)

Municipality	Annual Water Consumption (kWh/year)	Annual Entering Water (m^3/year)
TOTAL	***265 893 452***	***745 425 453***
AGERE	11 066 253	11 270 532
Águas da Azambuja	106 494	1 512 962
Águas da Covilhã	55 743	2 987 867
Águas da Figueira	2 766 150	4 162 073
Águas da Região de Aveiro	3 989 185	22 663 413
Águas da Teja	613 150	727 156
Águas de Alenquer	1 320 268	3 104 623
Águas de Barcelos	50 567	4 106 690
Águas de Carrazeda	335 600	588 026
Águas de Cascais	2 803 592	17 708 736
Águas de Coimbra	578 821	13 064 924
Águas de Gondomar	244 620	8 473 488
Águas de Mafra	2 026 582	5 881 262
Águas de Ourém	1 839 772	3 303 328
Águas de Paços de Ferreira	416 048	1 859 068
Águas de Paredes	211 317	1 849 424
Águas de S. João	942 177	1 714 888
Águas de Santarém	6 133 714	6 116 593
Águas de Santo André	218 736	1 301 640
Águas de Valongo	38 354	4 843 066
Águas do Lena	966 104	1 205 214
Águas do Norte	6 016 089	6 101 999
Águas do Planalto	1 871 386	3 284 586
Águas do Porto	121 156	21 077 709
Águas do Ribatejo	6 578 688	12 086 042
Águas do Sado	6 086 843	10 641 177
AMBIOLHÃO	166 654	4 082 260
Aquaelvas	989 572	1 412 433
Aquafundalia	99 738	1 773 913
Aquamaior	53 332	505 188
CM de Aguiar da Beira	87 108	507 189
CM de Alandroal	40 123	425 486
CM de Albufeira	509 127	11 248 387
CM de Alcácer do Sal	227 039	1 470 953
CM de Alcochete	644 292	1 457 551
CM de Alcoutim	110 931	292 242
CM de Alfândega da Fé	56 541	520 118
CM de Alijó	12 575	855 062
CM de Aljezur	90 900	890 381
CM de Aljustrel	21 705	1 109 073
CM de Almeida	12 563	719 475
CM de Almodôvar	50 114	413 202
CM de Alter do Chão	64 607	262 435
CM de Alvaiázere	16 560	628 470
CM de Amares	839 375	1 290 603
CM de Ansião	1 186 963	1 183 373
CM de Arcos de Valdevez	150 311	1 386 477
CM de Arganil	250 841	1 403 456
CM de Armamar	20 312	483 358
CM de Arraiolos	69 219	444 897
CM de Arronches	17 634	270 522
CM de Arruda dos Vinhos	250 543	1 205 021
CM de Avis	41 862	463 657
CM de Barreiro	2 801 370	5 377 378
CM de Bombarral	112 478	1 030 480
CM de Bragança	676 597	4 180 044
CM de Cabeceiras de Basto	429 124	1 703 424
CM de Caminha	35 845	1 560 625
CM de Castelo de Paiva	341 153	1 735 393
CM de Castelo de Vide	3 159	372 832
CM de Castro Marim	211 141	1 383 884
CM de Celorico da Beira	10 215	694 721
CM de Chaves	168 422	4 046 964
CM de Condeixa-a-Nova	181 970	1 474 732
CM de Constância	14 995	315 596
CM de Espinho	16 218	2 382 656
CM de Estremoz	1 236 179	2 226 172
CM de Évora	16 955	4 309 770
CM de Felgueiras	566 369	3 138 933
CM de Ferreira do Alentejo	454 856	926 350
CM de Ferreira do Zêzere	1 814	1 105 742
CM de Figueiró dos Vinhos	39 391	498 575
CM de Gavião	1 837	282 518
CM de Góis	443 794	507 564
CM de Golegã	552 381	690 363

Municipality	Annual Water Consumption (kWh/year)	Annual Entering Water (m3/year)
CM de Gouveia	3 915	857 451
CM de Grândola	10 737	1 082 416
CM de Guarda	168 083	3 030 140
CM de Idanha-a-Nova	130 340	1 529 238
CM de Lagoa	1 778 164	5 347 311
CM de Lagos	792 570	6 030 872
CM de Lamego	151 657	1 975 692
CM de Loulé	3 548 357	7 607 728
CM de Lourinhã	28 989	2 065 557
CM de Lousã	602 076	2 100 852
CM de Lousada	225 029	2 237 782
CM de Mação	166 333	1 274 774
CM de Macedo de Cavaleiros	72 415	2 797 265
CM de Mangualde	2 604 691	2 875 262
CM de Marinha Grande	2 312 706	3 736 813
CM de Marvão	15 338	394 962
CM de Mealhada	655 973	1 821 915
CM de Melgaço	224 526	600 464
CM de Mértola	302 949	612 328
CM de Mesão Frio	24 969	360 647
CM de Mira	735 190	1 405 054
CM de Miranda do Corvo	192 664	942 410
CM de Mogadouro	1 498 100	1 004 467
CM de Moimenta da Beira	621 767	1 218 051
CM de Moita	2 484 284	4 862 124
CM de Monção	720 778	1 140 469
CM de Montalegre	11 880 389	470 571
CM de Montemor-o-Novo	252 615	975 416
CM de Montemor-o-Velho	1 583 596	2 162 988
CM de Mora	902 956	516 978
CM de Mourão	83 241	274 713
CM de Nelas	93 061	1 148 278
CM de Nisa	2 232	552 055
CM de Óbidos	810 621	1 407 185
CM de Odemira	84 100	2 016 540
CM de Oleiros	20 358	494 443
CM de Oliveira de Frades	474 157	609 318
CM de Oliveira do Hospital	79 741	1 116 523
CM de Ourique	17 201	350 759
CM de Palmela	7 162 079	5 652 179
CM de Pampilhosa da Serra	40 875	346 788
CM de Paredes de Coura	32 236	784 591
CM de Pedrógão Grande	2 881	456 574
CM de Penacova	229 466	1 080 305
CM de Penalva do Castelo	146 507	551 140
CM de Penedono	204 398	258 877
CM de Penela	103 720	746 041
CM de Pinhel	27 028	759 643
CM de Pombal	5 526 988	3 792 594
CM de Ponte da Barca	50 570	606 557
CM de Ponte de Lima	168 990	3 302 873
CM de Ponte de Sor	501 862	1 338 732
CM de Porto de Mós	2 902 731	2 780 100
CM de Póvoa de Varzim	8 256	3 495 939
CM de Proença-a-Nova	5 961	753 155
CM de Redondo	44 908	574 921
CM de Sabrosa	162 181	618 875
CM de Sabugal	246 605	1 539 729
CM de Santa Marta de Penaguião	14 160	767 290
CM de Santiago do Cacém	135 384	1 843 804
CM de São Brás de Alportel	170 774	1 570 167
CM de São João da Pesqueira	58 614	728 190
CM de São Pedro do Sul	1 157 659	1 039 858
CM de Sardoal	4 400	388 457
CM de Sátão	722 802	841 896
CM de Seixal	7 250 767	12 250 448
CM de Sernancelhe	38 766	324 636
CM de Sertã	91 118	1 189 808
CM de Sesimbra	5 087 947	6 042 555
CM de Silves	360 244	4 757 798
CM de Sines	1 279 644	1 886 849
CM de Sobral de Monte Agraço	81 962	943 654
CM de Soure	1 295 136	2 157 149
CM de Tabuaço	89 389	637 927
CM de Terras de Bouro	23 568	1 244 567
CM de Torre de Moncorvo	162 244	883 681
CM de Vale de Cambra	1 717 896	728 906
CM de Vila de Rei	2 049 989	577 014
CM de Vila Flor	1 618 427	810 059
CM de Vila Nova de Cerveira	317 450	1 227 408
CM de Vila Nova de Famalicão	124 253	7 217 167
CM de Vila Nova de Poiares	258 667	739 940
CM de Vila Velha de Ródão	1 478	394 449
CM de Vila Verde	2 490 718	1 997 643
CM de Vimioso	1 030 241	574 497
EMAR de Portimão	951 926	7 359 393
EMAR de Vila Real	290 343	3 358 545
EMAS de Beja	62 209	2 804 254

Municipality	Annual Water Consumption (kWh/year)	Annual Entering Water (m3/year)
EPAL	32 308 985	93 475 536
FAGAR - Faro	1 180 664	5 799 614
Indaqua Feira	246 002	4 771 021
Indaqua Matosinhos	154 601	12 369 538
Indaqua Oliveira de Azeméis	81 853	2 090 037
Indaqua Santo Tirso/Trofa	29 882	2 723 020
Indaqua Vila do Conde	17 632	3 994 883
INFRALOBO	167 982	1 309 491
INFRAMOURA	351 171	4 309 436
INFRAQUINTA	182 805	1 652 135
INFRATRÓIA	1 886 442	1 142 870
INOVA	2 163 062	4 612 646
Luságua Alcanena	986 973	895 146
Penafiel Verde	6 527 155	2 727 712
SIMAR de Loures e Odivelas	5 652 000	27 968 419
SIMAS de Oeiras e Amadora	3 202 726	26 035 479
SM de Abrantes	3 050 085	3 897 795
SM de Alcobaça	2 987 882	4 911 463
SM de Castelo Branco	2 553	4 532 916
SM de Nazaré	832 327	1 853 699
SMAS de Almada	14 272 939	16 541 335
SMAS de Leiria	4 465 162	9 504 039
SMAS de Montijo	1 920 285	4 533 477
SMAS de Peniche	1 919 813	3 492 264
SMAS de Sintra	3 034 026	25 261 577
SMAS de Tomar	143 962	3 764 645
SMAS de Torres Vedras	527 342	5 432 012
SMAS de Vila Franca de Xira	2 166 396	10 264 912
SMAS de Viseu	7 972 134	8 902 963
SMAT de Portalegre	46 332	2 276 131
SMEAS de Maia	953 827	10 730 686
SMSB de Viana do Castelo	117 453	4 758 096
Taviraverde	131 358	2 447 535
VIMÁGUA	11 552 143	10 448 110

Appendix IIII – Economical Analysis of PAT implementation in Santa Cruz WSS

Discount Rate	6%	8%	10%	IRR 17.62%
NPV (€)	16 550.77 €	12 007.17 €	8 418.60 €	0.00 €
f	12.78	10.67	9.08	5.58
B/C	7.52	9.12	11.20	26.28

Year	Investment Cost	Maintenance Cost	Revenue	Cash-Flow	Cash-Flow	Cash-Flow	Cash-Flow
0	15 000 €	0		-15 000 €	-15 000 €	-15 000 €	-15 000 €
1	0.00 €	300.00 €	3 050.74 €	-12 404.96 €	-12 453.02 €	-12 499.33 €	-12 661.43 €
2	0.00 €	300.00 €	3 050.74 €	-9 956.81 €	-10 094.70 €	-10 225.99 €	-10 673.27 €
3	0.00 €	300.00 €	3 050.74 €	-7 647.24 €	-7 911.08 €	-8 159.32 €	-8 983.01 €
4	0.00 €	300.00 €	3 050.74 €	-5 468.40 €	-5 889.20 €	-6 280.52 €	-7 546.02 €
5	0.00 €	300.00 €	3 050.74 €	-3 412.88 €	-4 017.09 €	-4 572.53 €	-6 324.34 €
6	0.00 €	300.00 €	3 050.74 €	-1 473.72 €	-2 283.66 €	-3 019.81 €	-5 285.72 €
7	0.00 €	300.00 €	3 050.74 €	**355.68 €**	-678.63 €	-1 608.25 €	-4 402.73 €
8	0.00 €	300.00 €	3 050.74 €	2 081.53 €	**807.51 €**	-325.01 €	-3 652.04 €
9	0.00 €	300.00 €	3 050.74 €	3 709.69 €	2 183.56 €	**841.58 €**	-3 013.84 €
10	0.00 €	300.00 €	3 050.74 €	5 245.69 €	3 457.69 €	1 902.11 €	-2 471.26 €
11	0.00 €	300.00 €	3 050.74 €	6 694.74 €	4 637.43 €	2 866.22 €	-2 009.98 €
12	0.00 €	300.00 €	3 050.74 €	8 061.77 €	5 729.79 €	3 742.69 €	-1 617.82 €
13	0.00 €	300.00 €	3 050.74 €	9 351.43 €	6 741.23 €	4 539.49 €	-1 284.43 €
14	0.00 €	300.00 €	3 050.74 €	10 568.08 €	7 677.75 €	5 263.84 €	-1 000.98 €
15	0.00 €	300.00 €	3 050.74 €	11 715.87 €	8 544.90 €	5 922.35 €	-760.01 €
16	0.00 €	300.00 €	3 050.74 €	12 798.69 €	9 347.82 €	6 520.99 €	-555.15 €
17	0.00 €	300.00 €	3 050.74 €	13 820.22 €	10 091.25 €	7 065.21 €	-380.98 €
18	0.00 €	300.00 €	3 050.74 €	14 783.92 €	10 779.62 €	7 559.95 €	-232.91 €
19	0.00 €	300.00 €	3 050.74 €	15 693.08 €	11 417.00 €	8 009.72 €	-107.02 €
20	0.00 €	300.00 €	3 050.74 €	16 550.77 €	12 007.17 €	8 418.60 €	0.00 €