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Pump-as-turbines for hydropower energy recovery from on-demand irrigation networks: Flow fluctuation characterisation, energy potential extrapolation, and real-scale implementation.

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Declaration

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Summary

More water efficient irrigation techniques have been studied and developed during the last decades, and are becoming of significant importance in arid and semi-arid regions, as these are leading to more energy intensive irrigation infrastructures. This thesis presents hydropower energy recovery as a potential measure to improve the energy efficiency in on-demand irrigation networks. Findings in four main elements of work are developed, presented and discussed, related to: i) flow fluctuations prediction, ii) feasibility assessment, iii) energy potential extrapolation and iv) real-scale implementation.

On the first element, a new methodology to predict the in-pipe flow variations in on-demand networks along an irrigation season was developed. As fluctuations in the flow rate provokes considerable effects on turbine efficiency for hydropower energy recovery, this characterisation is largely important to quantify in detail the hydropower potential. Furthermore, the theoretical performance of pump-as-turbines was considered based on the theoretical best efficiency point, selecting the device returning the minimum payback period. Pumps-as-turbines are conventional pumps working in reverse mode as turbines. Using them for energy recovery has been shown to be cost-effective at sites with small power output capacity rather than conventional turbines. Their cost-effectiveness lies in the fact that pumps are mass produced and many models exist of differing sizes. This results in considerably cheaper machinery covering a wide range of flow and head combinations. However, anticipating their performance is a well-known challenge.

Secondly, the methodology feasibility was evaluated comparing the results predicted in nine points of an on-demand irrigation network with actual data recorded for the 2015 irrigation season. Several statistical parameters and efficiency criteria were used to compare the results coming from simulations and from the application of actual flow observations in a real network, in high resolution, and over a 1-year period. The validation of this methodology will allow its application in different irrigation networks to quantify the existing potential and study how PATs could improve their energy efficiency. The overall result of the methodology comparing actual records and predicted data was satisfactory. In the case of the flow, it presented a good fit between the predicted and the actual values, with a MAE and RMSE of 0.0026 and 0.0068 on the occurrence probability. Values for R^2 and efficiency criteria of 0.804 and 0.576 respectively, were obtained. Therefore, the results showed a feasible average accuracy for flow prediction, which allowed a more accurate estimation of the hydropower potential.

Once the method was developed and validated, a large-scale energy recovery assessment was carried out, which could provide an approximation of the potential benefits associated with hydropower in on-demand irrigation networks. Linear regression models and artificial neural networks were used to estimate the energy recovery potential in an irrigated surface of about 164,000 ha. Three proxy variables were used, including: irrigated surface, theoretical crop irrigation requirements and slope. Using the results provided by artificial neural networks, the economic, environmental and energetic impacts were quantified in the area analysed. A reduction in energy consumption in the agriculture sector of this magnitude could have significant impacts on food production and climate change. This was the largest scale assessment of hydropower potential conducted in irrigation networks to date with the next nearest being an assessment of 4,000 ha.

Finally, an experimental hydropower plant using a pump-as-turbine was designed and constructed in an actual on-demand irrigation network to supply energy to a local farm in Southern Spain. A 4 kW pump-as-turbine was installed in a by-pass, recovering around 20 m of head and turbining 30 $l\ s^{-1}$, connected to a bank of batteries that worked as backup for periods where no electricity generation was possible. The pilot plant was design using the methodologies developed in the earlier parts of the thesis. The plant supplied the energy demanded at the farm during the entire irrigation season, eliminating a diesel generator previously used to fulfil the energy demand. Significant benefits were achieved, exceeding €2,000 of economic savings and more than 8 t eCO_2. Lastly, an analysis of two pump-as-turbine regulation schemes (hydraulic and electric), and the global efficiency of the plant were carried out. The results obtained in this research could lead to a more efficient plant designs and a better understanding of PAT performance working under actual conditions in irrigation networks. Thereby improving the plant power and global efficiency, and sustainability of energy sources applied to the agriculture sector.

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List of Publications

Journal Publications:

1. M. Crespo Chacón, J. A. Rodríguez Díaz, J. García-Morillo, and A. McNabola (2019). "Pump-as-turbine selection methodology for energy recovery in irrigation networks: Minimising the payback period," *Water (Switzerland)*, MDPI, vol. 11, no. 1, pp 1-20.

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3. M. Crespo Chacón, J. A. Rodríguez Díaz, J. Garcia-Morillo, and A. Mcnabola (2020). "Estimating regional potential for micro-hydropower energy recovery in irrigation networks on a large geographical scale," *Renewable Energy*, 155, 396-406. https://doi.org/10.1016/j.renene.2020.03.143.

4. M. Crespo Chacón, J. A. Rodríguez Díaz, J. Garcia-Morillo, and A. Mcnabola. "Evaluation of the design and long-term performance of a micro hydropower plant in a pressurised irrigation network: real world application at farm-level in Southern Spain", *Renewable Energy (Under review).*

Conference Publications:

1. M. Crespo Chacón, J. A. Rodríguez Díaz, J. Garcia-Morillo, J. Gallagher, P. Coughlan and A. McNabola (2018). "Potential Energy Recovery Using Micro-Hydropower Technology in Irrigation Networks: Real-World Case Studies in the South of Spain." *Proceedings*, 679. 3rd International EWaS Conference: "Insights on the Water-Energy-Food Nexus", Lefkada Island, Greece 27-30 June 2018.

2. M. Crespo Chacón, J. A. Rodríguez Díaz, J. Garcia-Morillo, and A. Mcnabola (2019). "Pump-as-turbines for energy recovery: An attractive solution for auto consumption in agricultural farms". International Conference on Green Construction, 8-9 April 2019, Cordoba, Spain.

List of abbreviations

ANN	Artificial Neural Network
BEP	Best Efficiency Point
BPT	Break pressure tank
CO_2	Carbon dioxide
eCO_2	Equivalent Carbon Dioxide
E	Nash-Sutcliffe Model Efficiency
EPP	Excess Pressure Point
ER	Electrical Regulation
ET_o	Evapotranspiration
FAO	Food and Agricultural Organization of the United Nations
GHG	Greenhouse gas
HR	Hydraulic Regulation
IDAE	Diversification and Energy Saving Institute of Spain
IEA	International Energy Agency
MAE	Mean Absolute Error
MHP	Micro hydropower
MOM	Management, operation and maintenance
MSE	Mean Squared Error
PAT	Pump-as-turbine

PP	Payback Period
PRV	Pressure reducing valve
R^2	Coefficient of Determination
RIS	Relative Irrigation Supply
RMSE	Root Mean Squared Error
VOS	Variable Operating Strategy
VSD	Variable Speed Drive
WDN	Water distribution network
WWTP	Wastewater treatment plant

Nomenclature

a	Random scenario
AR_l	Annual revenues generated for the installation designed for the flow l
BT	Bernoulli Trial
C	Combinations of downstream open hydrants
C_{PPnl}	Total cost for a PAT with n magnetic polar pairs generator installation for the flow l
$days_j$	Monthly days
EV_j	Monthly experimental volumes
E_{lj}	Monthly energy recovered in the scenario l
H_{BEP}	Best efficiency point head
H_{lmPAT}	Head recovered for flow m in scenario l
IN_{ij}	Monthly water requirements per hydrant
N	Number of simulations
n	Number of downstream hydrants
n_{lj}	Monthly number of repeating times of the flow value l
p_{ij}	Monthly open hydrant probability
P_{lm}	Power for the scenario produced for the inlet flow m in the scenario l
$p_X(x)$	Mass probability function
$p(q_{lj})$	Monthly mass probability function of the flow value l

p_{cw}	Percentage of civil works in the total installation cost
PP_{nl}	Payback period for an PAT installation design for the flow l with a generator with n polar pairs
q_{max}	Design flow of the network
q_M	Maximum flow running in the pipe EPP studied
q_l	Value of the flow in scenario l
Q	Random variable Flow
Q_{lBEP}	BEP flow value in scenario l
Q_{lmPAT}	Flow running through the PAT when m flow is demanded in the scenario l
R_j	Monthly random vector [0-1]
r_j	Monthly energy tariff
t'_{ij}	Monthly hydrant irrigation time required
T'_{ij}	Monthly hydrant water availability
η_{max}	Maximum PAT performance
η_{lm}	Relative performance of the flow value m in the PAT designed for flow value l
γ	Water specific weight

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1 INTRODUCTION

The continued growth of the worldwide population has had an important effect on the demand for resources. One of the most significant impacts resides on the Water-Energy-Food Nexus, in which many investigations have been focused during the last years. The interconnection between these resources is such that the energy demanded for food production and supply chain was estimated at around 30% of worldwide consumption (Food and Agriculture Organization of the United Nations 2011). Moreover, one of the basic activities for food production, like agriculture, consumes for about 70% of freshwater globally (Mouraviev and Koulouri 2019).

On the other hand, the water sector was reported as one of the largest energy consumers, accounting for 4% (more than 100 Mtoe) of the global electricity consumption in 2014, used to extract, distribute and treat water and wastewater, with a predicted increase of 130% up to 275 Mtoe in 2040 (International Energy Agency n.d.). Thus, a change in any of the elements of this nexus could result in increase of the other two. For instance, the global population is estimated to grow up to 9.7 billion people by 2050, and this would suppose an increase of 60% in food demand, and so an increase for water and energy consumption. (FAO, 2015). This increase of food would have impact on the energy intake, which was predicted to raise up to 36% by 2035 from 2008 levels (International Energy Agency 2010).

Water and most of the activities related to it are indispensable for civilised society and sustainable development. Nonetheless, its current exploitation is not being carried out efficiently, neither from the energy sustainability nor the resource management points of view. The energy consumption associated with the operation of pressurized water networks represents around 2-3% of global energy consumption (Vilanova and Balestieri 2014). Water services are the fourth most energy-intensive industry in Europe. The energy dependency of the water sector is also reflected in the costs percentage represented by production and supply, which have risen up to 80% of operating budgets (Lofman et al. 2002). This trend of the increasing energy dependency makes the water sector responsible for significant contributions to climate change (Gallagher et al. 2015). It was reported that 5% of the CO_2 emissions in the US were related to the water sector in 2009, which would be translated in more than 62 coal fired power plants (Griffiths-sattenspiel and Wilson n.d.). This ratio increased up to 6% in India, where irrigation has an important weight (Shah 2009).

Contrary to this trend, the increasing pressure to counter the climate change impacts has led to the fixing of a set of global targets to reduce remarkably greenhouse gases (GHG) emissions. Such reductions were established to achieve 20% reduction by 2020 compared to 1990 levels and almost completely by 2050, as well as improving the energy efficiency by 20% (European Commission 2010).

Among the different activities within the water sector, agriculture is the most significant user of water resources worldwide, accounting for around 70% of all water use, and close to 95% in some developing countries (FAO - Food and Agriculture Organization of the United Nations 2015). This issue has made awareness of improving water efficiency in agriculture important. The modernization process carried out in the irrigation sector in some western countries, in either hydraulic infrastructure or in irrigation devices, has led to an improvement of water-resource use efficiency (Rodríguez-Díaz et al. 2008). The modernization of the hydraulic infrastructure normally implies the replacement of open channels with a pressurised pipe networks. One example of the magnitude of the improvement of water efficiency that could be achieved with this upgrade was shown in the Spanish National Plan for Irrigated Areas (Ministry of Food 2001), which expected to save about 3,000 Mm^3 per annum. As a proof of the results accomplished, Fernández García et al. (2014b) stated that the water demand in five irrigation districts in Southern Spain decreased by 23% on average comparing levels before and after the modernization.

This process has also resulted in an increase of the irrigation districts' energy consumption. In pressurised irrigation networks, energy reaches around 40% of the total water costs, and therefore water and energy efficiency cannot be considered independently (Rodríguez-Díaz et al. 2011). Blanco (2009) carried out a study in 10 irrigation districts, where the energy efficiency was analysed. It was estimated that the energy cost was around 20-30% of the total water costs, and the consumption per unit-irrigated surface had increased from 600 kWh ha^{-1} to 1,600 kWh ha^{-1}, before and after the modernization. These costs reached an important weight in some networks, amounting to 65% of the water cost (Fernández García et al. 2014b). Thus, the upgrade process has led to an increase of the water use-efficiency, whilst increasing the water cost.

Areas of excess pressure are unavoidable in pressurised irrigation networks, unless it is situated in an area with uniform gradient and demand distribution due to changes in elevation and demand across a typical irrigation network. The existing overpressure in pressurised water networks has given rise to the utilization of hydropower technology for energy recovery. Its use and furtherance would help to decrease the agricultural water fossil and carbon energy dependency, with no impact in the water supply (McNabola et al. 2014b). In addition, the irrigation devices (drippers, sprinklers) continue to evolve towards greater efficiency in the consumption of water and energy. This results in a lower working pressure requirement in some areas of an irrigation network, triggering the potential for available energy recovery. Therefore, both economic and environmental advantages could be achieved implementing such technology in irrigation: through the reduction of water and food costs; and reducing GHG emissions. However, the small power outputs typically found in these networks, most of them encompassed within the micro hydropower (MHP) range (5 to 100 kW), has led to the need to seek new economically viable hydro turbines for this particular setting.

Pump-as-turbines (PATs) were presented as a cost-effective technology for such micro power ranges, whose cost supposed potentially 10% of the cost of conventional turbines (Carravetta et al. 2014a; Fecarotta et al. 2014b; Lydon et al. 2017a; Novara et al. 2019; Power et al. 2014; Ramos, H.M.; Borga, A.; Simão 2009). As such, PATs have shown a considerable cost advantage for micro applications. However, despite a high nominal peak efficiency under best performance conditions, PAT efficiency dramatically drops with large flow fluctuations, which are quite common in irrigation networks due to the stationarity of the activity. It can be perceived how flow variability is a crucial factor for this technology and its design, as it will affect operational performance and viability (Lydon et al. 2017b).

The complexity of the design process for a PAT installation ensuring viable operation becomes even greater in irrigation due to the lack of flow fluctuations information. Although there is a high control of the network operation and the farmers' volume consumption are recorded and controlled to not exceed the fixed volume assigned by the water authority and regulate the water payments, it is uncommon to have devices measuring the condition variations of the network installed (i.e. flow meters). Besides the difficulties found for PAT installations analysis and design in irrigation networks, another consideration should be taken into account: how the long-term performance could affect the purpose for which the plant was projected. Changes in demand patterns, crops or climatic parameters (rainfall and evapotranspiration), for instance, would affect the setting operation, and hence to the viability of a PAT in an irrigation setting. This fact requires analysis of real-world installations, which would lead to an improvement in future plants.

1.1. Research objectives

Throughout the underlying objectives completed in this thesis, the main target was focused on the assessment and analysis of PAT potential to improve the energy efficiency in irrigation networks or bring energy to remote locations with no access to electricity. Based on this, the general objectives aforementioned are resumed below:

1. Gather information on, build and calibrate hydraulic models of pressurised irrigation networks.
2. Develop an accurate prediction method of flow variations and energy recovery quantification along an irrigation season.
3. Contrast the accuracy of the flow forecasted against measured field data.
4. Conduct a large-scale forecast of potential energy recovery in a region and evaluate the economic and environmental benefits and market potential.
5. Define a new approach to estimate the costs of a PAT installation in irrigation networks.
6. Design and construction of a full-scale demonstration plant in the field.
7. Design guidelines and support tools for PAT installation in irrigation networks.
8. Monitor and assess the long-term performance and viability analysis of an actual plant compared to predicted results.

1.2. Research contribution

This research will contribute theoretically and practically to the existing literature and knowledge. Theoretical contributions will be achieved through paper publications in scientific journals and conference proceedings. These will help to extend the existing literature on the topics of energy recovery in irrigation networks using PATs and design of these installations to decrease the energy dependency. Among the different papers written from this research, a summary of them and their status is outlined below:

Paper 1: *Pump-as-Turbine selection methodology for energy recovery in irrigation networks: minimising the payback period*.

This paper was published on 20th January 2019 in the open access journal Water, within the section Water-Food-Energy Nexus in the special issue “Modelling and Management of Irrigation System”, 11 (149), pages 1-20. The full reference to this paper is given in the list of publications section.

The paper presents a new statistical methodology to predict the flow variability in on-demand irrigation networks based on the possible combinations of open and closed hydrants and assesses the energy recovery potential in pre-selected points, identifying the PAT returning the minimum payback period.

Paper 2: *Hydropower energy recovery in irrigation networks: validation of a methodology for flow prediction and pump-as-turbine selection*.

This paper was published on 26 September 2019 in the journal Renewable Energy, within the issue 147 (2020), pages 1728-1738. The full reference to this paper is given in the list of publications section.

The paper applied the methodology developed in paper 1 in an on-demand irrigation network, comparing the results obtained for flow variability with actual flows, recorded hourly at the network. The paper aimed to validate the method through measuring some statistical performance indicators. The energy recovery potential was then evaluated and the PATs selected for both regimes, comparing the results gathered for predicted and recorded flows.

Paper 3: *Estimating regional potential for micro-hydropower energy recovery in irrigation networks on a large geographical scale.*

This paper was published on 24 March 2020 in the journal Renewable Energy, within the issue 155 (2020), pages 396-406. The full reference is given in the list of publications section.

The paper showed an innovative methodology to estimate the energy recovery potential in large geographical scale in regions with on-demand irrigation networks. The prediction models presented were linear regression models and non-linear methods. The proxy variables used were easily gatherable, encompassing irrigated surface, orographic, agronomic and climatic data. It was applied in two regions in Southern Spain (Cordoba and Seville), which encompassed more than 25,000 km^2 and an irrigated surface of almost 200,000 ha, to estimate the energy recovery potential. This is the largest assessment of this kind conducted to date.

Paper 4: *Evaluation of a micro hydropower plant design and performance in a pressurised irrigation network: real world application in Southern Spain.*

This paper is currently under review in the Journal of Cleaner Production.

The paper presented the design phase and considerations taken into account during the design of an actual PAT installation for self-consumption of energy recovered in a working agricultural farm. The plant performance was assessed during a full irrigation season, evaluating the environmental and economic benefits achieved. As a main achievement, the plant was capable of supplying the entire power required by the farmer.

The content of these papers will be described more in details in the following chapters of the thesis. Practical contributions will be made through the construction and analysis of an experimental demonstration plant, whose results will be used and disseminated to foster this technology within the irrigation sector. Detailed data is recorded by a sophisticated monitoring system, which will allow an itemized analysis of the input and output variables used for the plant design.

The subsequent content of this thesis is distributed as per the following chapters' structure.

Chapter 2 gives a comprehensive review along the existing literature covering two main fields: irrigation and hydropower. Irrigation was etymologically introduced, defining its origin and traditional techniques. A brief conceptualization of on-demand irrigation networks and how they are designed has been presented. A careful critical review of the key literature dealing with the problematic of the energy dependency in irrigation networks, and potential solution proposed have been discussed. Hydropower and pump as turbines as a measure to counteract this issue in urban water supply networks have been discussed. Based on the thesis's objectives defined, the literature review process identifies the gaps and areas towards which the research should be extended.

Chapter 3 introduces the overall research model adopted in the thesis and explains the inherent methodological approach. The different work stages in which the thesis is divided and required to fulfil the thesis's objectives are outlined.

The next four chapters present the research work carried out in the different scopes of the thesis, including;

Chapter 4 describes the methodology developed to predict the flow fluctuations needed to assess PAT installations, and estimate the energy recovery potential in pre-selected points at on-demand irrigation networks.

Chapter 5 validates the previous methodology comparing predicted flows with actual values recorded hourly.

Chapter 6 shows an innovative method to estimate the energy recovery potential on a large geographical scale for areas using on-demand irrigation networks using artificial neural networks.

Chapter 7 presents the design, construction and post-construction performance assessment of an actual PAT installation used for self-consumption in a farm within an on-demand irrigation network.

Chapter 8 discusses the main results and discoveries exposed along the four previous chapters, showing the limitations and potential impact of the findings.

Chapter 9 finishes this thesis presenting a set of conclusions to which the findings and results led, and recommends potential future research to carry irrigation towards becoming a more sustainable activity.

2 LITERATURE REVIEW

2.1. Introduction

This chapter presents a critical review of the literature in two main fields: irrigation and hydropower. Due to the differences found between the irrigation systems used in arid and semiarid, and in more mild temperate climates, the first part of the chapter deals with irrigation. Different definitions, origin and development, techniques employed, types of infrastructures or effects to which the replacement of the systems has led to, are explained among other points. On-demand irrigation networks are the systems assessed in this research; therefore, they have been introduced in this chapter. One key point which has arisen is the energy dependency that pressurised networks entail. The different impacts arising and solutions already proposed to this issue have been analysed here. As hydropower application in general and PATs in particular, have been widely studied in the water industry in previous research, an introduction to the literature related to this is also shown. PATs and their main characteristics, strengths and weaknesses have been introduced, as well as the different methods to anticipate their performance. The overarching aim of this research is to improve the energy efficiency in on-demand pressurised irrigation systems using hydropower solutions through PAT installation, estimating the existing potential, developing prediction methods for flow fluctuations, and extrapolating the results obtained in single networks to larger geographical scales, and implementing the solution proposed into a real working network.

2.2. Irrigation

Irrigation is one of the oldest and most fundamental activities in human history, representing the basis for ancient civilizations and being linked to their development. The definition of irrigation related to agriculture can be found in the different dictionaries as follow: "*the watering of land by artificial means to foster plant growth*" (*Merriam-Webster Dictionary* n.d.); "*the action of supplying land with water by means of channels or streams; the distribution of water over the surface of the ground, in order to promote the growth and productiveness of plants. Also, the part which is irrigated*" ("Oxford English Dictionary" n.d.); "*the practice of supplying land with water so that crops and plants will grow*" ("Cambridge English Dictionary" n.d.). It could be comprehended that irrigation intends to complement or replace artificially the crop's water requirements, fulfilling that which is not supplied naturally by rain or other means. Along the present chapter, an overview of irrigation history, hydraulic infrastructure and the different kind of practises will be explained.

2.2.1. A brief overview of the origins of irrigation

The origin of irrigation goes back for about 8,000 years, dating to the first archaeological records of irrigation farming in 6,000 B.C. at the Jordan Valley (Sojka et al. 2002) and the irrigation schemes used for its practise around the 5,000 B.C. (Bazza et al. 2006). The first civilizations using these water structures were the Egyptians and the Mesopotamians, who used the floods of the Nile, Tigris and Euphrates rivers to provide water to the crops cultivated.

During the initiation of irrigation the Ancient Egyptians constructed flat basins at the Nile banks, where the crops were grown and took the advantage of the floods to supply them with water. This technique was modernised building networks of parallel and perpendicular earthen banks and using regulated sluices that the floodwater was driven into a basin, remaining there until the soil was saturated. Then, the leftover water was drained and these lands used to cultivate the crops (Goblot 1963). This process can be seen in Figure 2.1. Mesopotamians used the different riverbed levels of the Euphrates and Tigris for irrigation and drainage. As the Euphrates bed was considerably above the alluvial plain, it was used as supply. In contrast, the lower level of Tigris bed provided a drain, where the lands in between both river were used for the cultivation of crops (Bazza et al. 2006; Britannica n.d.).

These techniques were expanded towards other Mediterranean regions, arriving to the Roman Empire in the second century B.C. Romans were focused on water management, for which they developed several hydraulic infrastructures. Some of them are even used for current irrigation practices. Among them could be found: masonry dams with derivation canals; reservoirs and cisterns to store rainwater; and canals and aqueducts for water conveyance (see Figure 2-2). The technique has been expanded worldwide and has kept evolving along the centuries, being nowadays the largest water consumer worldwide by far.

Figure 2-1. *Roman aqueduct in Segovia (Spain) in top; Dam constructed by the Romans between the first and second century A.D. in Spain, still in use in bottom.*

2.3. Irrigation infrastructure and techniques: Modernization process

Some of the ancient infrastructures that have been used for thousands of years and are still employed to manage and apply the hydraulic resources, being fundamental to preserve the irrigation activity and food production. Although they incorporate some recent technologies to either catch water from any source (i.e. river) or boost it (pump) to wherever is required. However, once the technique was extended and became a regular and essential practise, the efficient employment of water and management of water resources gained weight, especially in those warm countries with low precipitations. The continuous evolution of the irrigation techniques has given a wide variety of infrastructure for water conveyance and distribution, among which irrigation ditches, canals, weirs, water mills or pipelines, could be found.

The traditional infrastructure associated with water distribution in irrigation could be recognised as open surface flow constructions (i.e. canals or ditches). The conveyance efficiency were reported to reach values of approximately 60% - 70% using these (Rodríguez-Díaz et al. 2008). The type of irrigation traditionally practised was based on the flooding of the land where crops were cultivated, which led to an excess demand of water, i.e. the amount of water provided was in excess of requirements and the loss of water in conveyance added to inefficiency in resource use.

Combining water stress, the conveyance efficiency of this free surface stream constructions, and the excessive amount of water employed during the practise gave rise to the need of more efficient and productive means and techniques. This could be accomplished through a modernization of the hydraulic infrastructure, as well as of the devices employed. The modernization generally implies the replacement of open surface infrastructure by pressurised pipeline network. In a semiarid and irrigation-intensive country such as Spain (over 3,000Mha irrigated) important water savings have been achieved since the Spanish National Plan for Irrigated Areas (Ministry of Food 2001) as aforementioned, reaching 21% from 1950 to 2007 (Corominas 2010).

Pressurised networks allowed the change in the irrigation techniques, passing from surface to sprinkler or localized irrigation, which are more water efficient. However, the distribution in 2012 of these three techniques all around the world showed a huge predominance of surface irrigation over the others, encompassing 86% of the global irrigated land, against 11% for sprinkler and 3% for localized (FAO - Food and Agriculture Organization of the United Nations 2014). These are described below:

2.3.1. Surface irrigation

Surface irrigation is the oldest and most common method of applying water to croplands. Also referred to as flood irrigation, the essential feature of this irrigation system is that water is applied at a specific location and allowed to flow freely over the field surface, and thereby apply and distribute the necessary water to refill the crop root zone. This can be contrasted to sprinkle or drip irrigation where water is distributed over the field in pressurized pipes and then applied through sprinklers or drippers to the surface. Surface irrigation has evolved into an extensive array of configurations that can broadly be classified as (Kay, 2009):

- Basin irrigation.
- Border irrigation.
- Furrow irrigation.

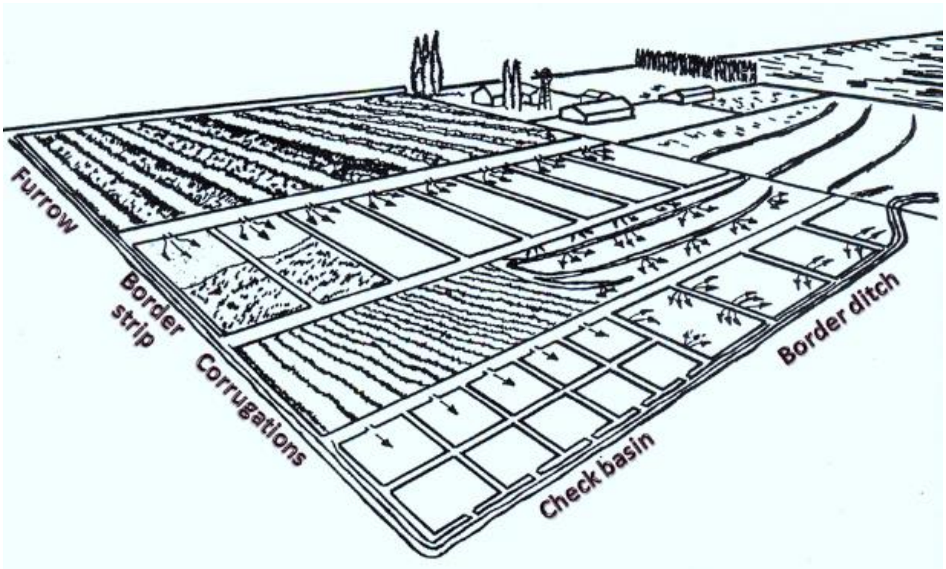

Figure 2-2. *Surface irrigation methods sketch (Kay, 2009)*

2.3.2. Sprinkler irrigation

In this method water is sprayed, falling on the soil somewhat resembling rainfall. The pressurised water reaches small orifices or nozzles, from which is sprayed. The pressure is usually obtained by pumping or through gravity. With careful selection of nozzle sizes, operating pressure and sprinkler spacing the amount of irrigation water required to refill the crop root zone can be applied nearly uniform at the rate to suit the infiltration rate of the soil.

2.3.3. Localized irrigation

Drip irrigation involves dripping water onto the soil at very low rates (2-4 liters/hour) from a system of small diameter plastic pipes fitted with outlets called drippers. Water is applied close to plants so just the part of the soil in which the roots grow is wetted unlike surface or sprinkler irrigation. It is considered as the most advanced and water efficient irrigation method, leading to significant water savings.

Figure 2-3. *Sprinkler irrigation*

Figure 2-4. *Drip irrigation*

Thus, the modernization of infrastructures implied an improvement in the water conveyance efficiency, reaching values close to 100%. This means that the water delivered by the water network is the same as the amount of water introduced in the system. This fact together with the reduction of the water applied in the field has led to significant water savings.

2.3.4. Irrigation Districts or Communities

Before describing the effects brought about by the pressurised infrastructure, and as a remarkable amount of the information and input data in this research is based on Southern Spanish irrigation networks, it may be useful to provide an explanation of their structure, design and operation.

The irrigator's communities (CCRRs) could be defined as "*association of landowners of irrigation areas, who unite obliged by law, for the autonomous and common administration of the public water, without the intention of profit. Thus, we are talking about a specific area suitable for irrigation, which benefits from a water concession available for its irrigators* " (Del Campo 2006). The main aims of these associations are focused on the distribution and management of water resources. The main reason of these communities to exist resides on the employment of common goods to irrigate, such as water itself or water networks used for the distribution.

The organization of irrigated land in term of associations is strongly sustained by the Spanish Water Law, which imposes the requirement for different water users utilizing the same water outlet to create these users communities. This is referred in the Article 81.1 of the Legislative Royal Decree 1/2001. Some of their properties are directly related to the hydraulic resources management and exploitation, as the control on the abuse of water resources by any user or to facilitate the collection of the users' costs to the Government, among others (Del Campo 2006).

The origin of these bodies goes back to the Roman age in Spain, where the farms were distributed around the different hydraulic infrastructure of the time. Over time, the infrastructure employed for the water distribution has been changing, as aforementioned, improving their efficiency. The large irrigation networks began to operate more than 50 years ago, replacing the traditional irrigation systems by the 70s of the previous century. Thus, during the last decades the CCRRs have been substituting the referred open channels for pressurised irrigation networks. This trend can be shown in numbers, comparing the surface irrigation level between 2000, where it was 59% of the irrigated land, and 2017 where this ratio decreased down to 24.8%. On the other hand, the percentage left by the surface irrigation was occupied by localized (drip) irrigation, which suffered an increase from 17% in 2000 to 51.4% in 2017, raising up by more than 1 million ha (Del Campo 2006).

Importantly for this thesis we distinguish between the large scale irrigation districts or networks which are operated by CCRRs (typically pipe diameter over 1200mm), and farm-level irrigation. Farm-level irrigation occurs beyond the hydrants of the irrigation district or network, and involves water flows and infrastructure of a smaller scale. Later research examines the resources for and viability of PAT installation within the irrigation district (see Chapters 4-5) and at farm-level (see Chapter 7) separately.

2.4. Pressurised irrigation networks

A pressurised irrigation network is a system concerned with distributing water under pressure from the water source to the irrigated lands. The main differences found with traditional surface irrigation falls on the operation and applied flow for both systems, as well as the on the energy dependency of the pressurised systems.

Therefore, the main differences related to the flow are; the flow rate in pressurised systems is significantly smaller than in open channels, reaching values close $1 m^3 h^{-1}$. In addition, free surface flow systems convey the water by gravity as per the field contours, whilst the pipes systems follow the most convenient route. Regarding the volume provided by unit irrigated area, traditional systems apply larger volumes than pressurised systems, which distribute the water in small rates in larger areas (Phocaides 2007).

Independent of the scale of the network and irrigation technique and devices employed, all pressurised networks count on a common set of elements, such as: head control station, main or transmission pipelines, hydrants, feeder pipes and irrigating pipes where the irrigation devices are connected (at farm-level) (Phocaides 2007). Large irrigation districts/networks normally comprise a group of different farms, each of which has its own farm-level irrigation system, following after the hydrants of the districts network, as the farm is owed by the farmer, while the network (including hydrants) is part of the water user association (irrigation community). Therefore, the farmer decided the type of irrigation technique to use, and thus the emitters to be installed, as explained below. The following elements commonly apply:

- The water source usually corresponds to the catchment zone in a river or a dam.
- The head control unit is the responsible for the control of the discharge and pressure in the entire system. The control head function is carried out by either a pumping station or a reservoir, by setting the manometric head or the elevation respectively.
- The main pipelines, or transmission pipes, are the largest diameter pipes, able to convey the maximum flow for which the network was designed.
- Submains pipes: used for water distribution purpose, they compose the branches, with smaller diameter than main pipes.
- Hydrant: It is an integrated shut-off valve system to ensure the water supply, either of the whole flow for which it is designed or just part of it.
- Mainfolds: Smaller diameter pipelines at the outlet of the hydrant used to feed the laterals (farm-level).
- Laterals: perpendicularly fitted to the mainfolds, placed along the plants where the emitters are connected (farm-level).
- Emitters: These are the responsible to discharge the water. There are different kind of emitters, depending on the technique employed for the discharge, among could be found: drippers, sprinklers, sprayers, etc (farm-level).

A general scheme layout showing the main elements of a pressurised irrigation network can be seen in Figure 2.5. In addition, real pictures of various elements are shown in Figure 2.6 – 2.9.

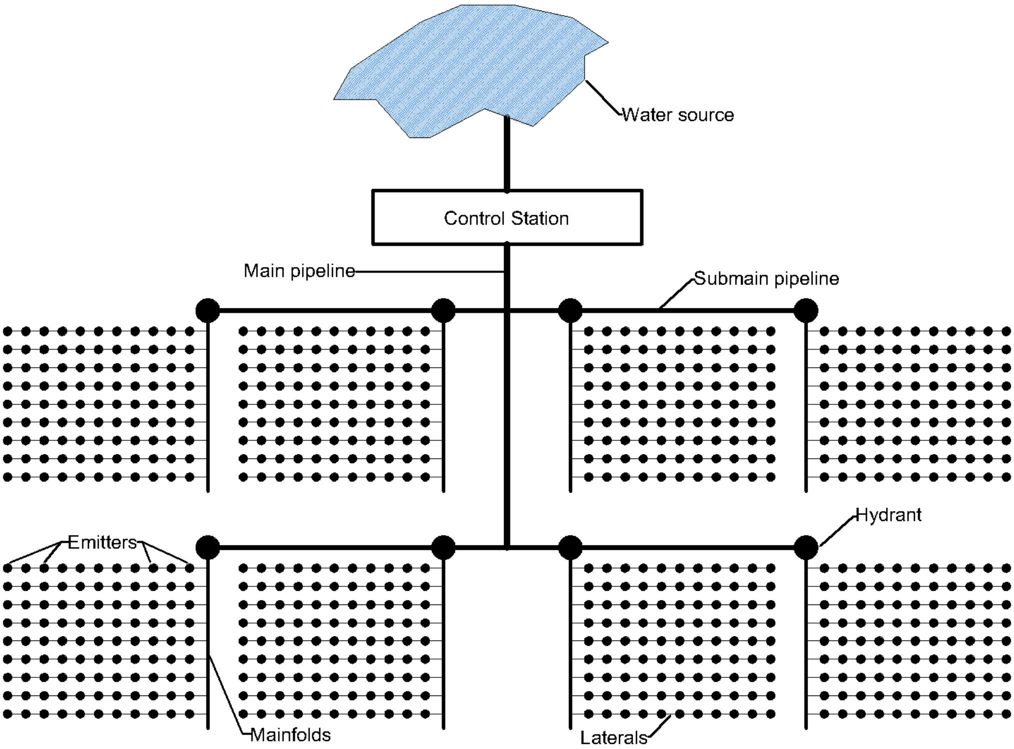

Figure 2-5. *General scheme and elements of a pressurised irrigation network*

Figure 2-6. *Pumping station (head control unit)*

Figure 2-7. *Main pipelines during construction*

Figure 2-8. *Irrigation hydrant*

Figure 2-9. *Double layer drippers (emitters)*

2.4.1. On-demand irrigation networks

In order to guarantee the same rights to every farmer using and irrigation network, the large traditional systems shared out the water attending to some crops rotation criteria. These systems have the disadvantage of not always applying irrigation water when required due to availability issues, directly affecting to the crops' yield. The main effects of a low production affect to the farmers, who might not obtain the seek harvest, which could lead to economic losses.

The risk of having losses due to the lack of water is the starting point for the known as on-demand irrigation networks. In these irrigation systems, the water is available 24 hours per day, being the farmer the person deciding how much water should be used and the moment of application. These infrastructures provide a much wider flexibility in the water use, which increase the farmers' likelihood of improving their benefits. The tariff applied to each farmer generally is divided into two different parties: the canon and tariff that is a fixed cost per unit irrigated area; the electricity cost, which is variable and depends on the total water consumed during an irrigation season, which trends to increase as the water withdrawn does. The volume is usually measured at the devices installed at the farms for the water delivery, the aforementioned hydrants, which count with a cumulative flow meter.

The design must be done adequately in order to ensure the minimum pressure required at the hydrants. Due to the large scale of these systems and different head requirements at the different farms, hydrants are normally equipped with other devices, such as flow control valves or pressure reducing valves to control the inlet conditions prior irrigating. The continuous water availability at on-demand irrigation networks increases the complexity of their design, as the farmers' freedom to open or close the hydrants makes the calculation of the discharges flowing in the network a challenge. Furthermore, the network has always to satisfy the hydrant requirements of demand and pressure.

The flows' volatility is very significant in on-demand networks, as the discharge varies as the variables do. Hence, there are periods in which the demand is quite low or null, while massive flows are demanded in other periods. The spatial and temporal flow variation depends mainly on three aspects: the crop patterns, the agro-climatic parameters (rainfall and evapotranspiration) and the farmers' habits. The different crops cultivated at the farms irrigated by the network have different irrigation needs in the different annual season. Considering the rainfall and evapotranspiration, these needs could increase or decrease. Furthermore, each farmer has the flexibility to apply the water when it suits better. Therefore, the discharge will vary as per the combination of all these variables. These variations have to be taken into account in the design phase.

Lamaddalena and Sagardoy (2000) divided the parameters to be considered in the design of an on-demand network in two classes: Environmental and decision parameters. While the first ones cannot be modified and depends on the area, the second ones depends on the designer decisions. Among the environmental parameters, the most important are: climate and pedologic conditions, agriculture structure, socioeconomic farmers' condition or type and location of water source. The decision parameters are related to the crops cultivated, irrigation technique used and their requirements and to the properties of the network, such as number of hydrants, design discharge per hydrant or delivery schedule.

Traditionally, the design of on-demand irrigation networks has been based on statistical distribution of peak flows. The most employed method was proposed by Clement (1966) more than 50 years ago.

Clèment came up with a probabilistic method to estimate the flow in pipes, supposing a random distribution of these, which depended on the number of hydrants of the network and their design flow (d) in l s^{-1} ha^{-1}. Each hydrant could be open or closed in a specific moment, being unlikely that all the hydrants were open at the same time. Therefore, each pipe was sized using the maximum flow that corresponded to the product of number of hydrants and the design flow. Thus, the flow running in each line is a random variable obtained from the sum of the binomial random variables associated to each hydrant (as they have two possible outputs; open or closed).

From the Clèment method, it could be extracted that for a high number of hydrants, the flow running in each pipe follows a normal distribution. The first Clèment formula is expressed as Equation (2.1). Where Q is the flow circuiting in a pipe, N is the number of hydrants open downstream, p is the probability of a hydrant to be open, d is the design flow for each hydrant and U is the typified variable corresponding to simultaneity index (number of hydrants that could be open at the same time) given at the Table 2.1.

The probability of a hydrant to be open (p), defined in Equation (2.2), is estimated as the relationship between irrigation time required to fulfil the crops water requirements for a given time period (t'), and the total time for the same period, (t'').

$$Q = N \cdot dp + U\sqrt{p(1-p)Nd^2} \tag{2.1}$$

$$p = \frac{t'}{t''} \tag{2.2}$$

Table 2-1. *Values of U (typified variable) depending to the simultaneity index*

Simultaneity (%)	U
90	1.28
91	1.34
92	1.41
93	1.48
94	1.56
95	1.65
96	1.75
97	1.88
98	2.05
99	2.33
99.5	2.58

Where Q is the flow circuiting in a pipe, N is the number of hydrants open downstream, p is the probability of a hydrant to be open, d is the design flow for each hydrant and U is the typified variable corresponding to simultaneity index (number of hydrants that could be open at the same time) given at the Table 2.1.

However, the method considers some incorrect hypotheses, such as the permanent flow rate at the hydrant, independent of the pressure available or hydrants open in the network. This behaviour is not followed in actual networks.

Besides the Clèment methodology, other methods have been proposed for the design of on-demand irrigation networks. De Boissezon and Haït (1965) used the formula proposed by Clèment, but introduced some changes to it, taking into account two main points: i) difference between hydrant requirements and their open/closed likelihood; ii) the statistical approach was only applied in the main pipelines, while the small pipelines directly used the sum of all the hydrants downstream working at the same time.

Mavropoulos (1997) proposed a new formula to obtain the peak discharges based on the Weibull distribution. The author compared the demands with Weibull and normal distribution, where the first one fitted the actual demands for a period of three years, whilst the second fitted just for two years period.

Rodríguez Díaz et al. (2007) developed a model able to simulate and calculate the flows circulating in the network at any time during the irrigation season, concluding that a gamma distribution would fit better than normal and Weibull distributions.

In the last years, several research works have been focused on the computational simulation of flows to analyse the behaviour of the networks. Granados Garcia (2013) classified in two main groups the techniques investigated using the tool aforementioned:

i) The first ones are related to the peak flows, consisting of running an extensive number of simulations under different random network performance hypotheses. The results obtained could be used to design the network and define energy saving strategies. Among others, application of flow control valves in hydrants to simplify the network design and reduce the construction costs, optimization algorithms to minimize the construction and exploitation costs using economic series methods, simulation models to obtain the daily volumes and hourly discharges at hydrants or new stochastics methods to get more accurate design flows (Alandi et al. 2001; Alandí et al. 2007; Khadra and Lamaddalena 2006; Moreno et al. 2007b).

ii) The second group are related to the network assessment to ensure the demands, having been developed by research on the feasibility of the network (non-failure) or evaluation of the potential failures (i.e. lack of pressure) (Rodriguez-Díaz et al. 2012; Juana et al. 2009; Pereira et al. 2003; Pérez Urrestarazu et al. 2009, 2010). However, these studies reached similar results while presenting a greater application complexity.

Clément’s methodology for designing on-demand irrigation networks has been globally accepted by many experts in the field, since it has been defined as a simple and flexible method, which provides good approximate values, returning quite feasible results. Monserrat et al. (2004) compared the values obtained after applying the Clèment method with real data to assess how both fitted. Although the discharge distributions did not match (real flows did not follow the normal distribution), the accumulated probability for the flow domain had differences lower than 9.4%. This indicates how the cumulative flow distribution for an entire irrigation season obtained using Clèment is almost the same as the actual one. Although better results were obtained using other distributions, several authors concluded that the Clèment method was a good design approach (Monserrat et al. 2004; Rodríguez Díaz et al. 2007). Furthermore, it was also stated that Clèment's formula generally adjusted better than Mavropoulos, particularly for a small number of outlets, when a simultaneity index of 95% or 99% was used (Rodríguez Díaz et al. 2007; Verschaeren 2000).

2.4.2. Effects of the modernization process

More water efficient techniques have been studied and developed during the last decades. Traditional irrigation methods (open surface channels and ditches) have been replaced by pressurised irrigation techniques, such as sprinkler or localized irrigation, which encompassed 14% of the total irrigated area globally in 2014 (FAO - Food and Agriculture Organization of the United Nations 2014). This percentage varied depending on the country analysed, reaching values of half of the irrigated area in the US, while decreasing in other regions such as India or China. However, this trend is changing, since China and India were the countries where localized irrigation gained the most weight in the last two decades, expanding by 88 fold and 111 fold respectively (National Geographic 2012). In Mediterranean regions, the area represented by pressurised irrigation was even over half of the irrigated surface in 2013 levels, accounting for about 60%, and reaching 100% in some countries (Daccache et al. 2014). Looking to the global perspective, the expansion of drip irrigation kept the same trend, where the drip irrigated surface passed from around hundred hectares to around 10.3 million from 1974 to 2012 (FAO - Food and Agriculture Organization of the United Nations n.d.; National Geographic 2012). The new irrigation methods supposed an improvement in water use efficiency, while increasing the energy dependency.

Several studies on this field estimated the water saved using pressurised systems. Rodríguez-Díaz et al. (2011) assessed the water consumption before and after the modernization process carried out at the Bembezar Margen Derecha irrigation district. The district used to employ an open surface distribution (channel) as the main network to irrigate around 12,000 ha of crop lands with 1,300 users, whose loses were approximately 25%. The surface irrigation was practised in over 70% of the land irrigated, with just small portions of drip irrigation in few farms where the farmer employed their own reservoirs, pumps and pipes to pressurise the water. When the pipeline system replaced the open surface network, the water savings achieved overpassed 40% of the annual volume employed, passing from 8,000 m^3 ha^{-1} to 4,700 m^3 ha^{-1}.

Another research focused on the modernization effect on water savings was carried out in five irrigation districts, which passed also from open surface to pressurised systems. The average results showed how the annual irrigation water supply volume decreased by more than 20%, reaching values close to 40% in some cases (Fernández García et al. 2014b).

It can be seen how important amounts of water were saved passing from open surface networks to pressurised systems. However, this achievement in water use efficiency had an impact on the energy consumption and water cost. Various researchers had been focused on the effect of the modernization on this issue, assessing how the pressurisation of irrigation networks influenced the energy efficiency, how the cost of energy had repercussions on the farmers' water costs, and hence in the food production cost.

Rodríguez Díaz et al. (2011) studied how the modernization had affected water and energy consumption in more than 58,000 ha distributed in 10 irrigation districts distributed all around Andalusia, Southern Spain, concluding that the average power required per unit-irrigated surface increased by up to 1.56 kW ha^{-1}.

Fernández García et al. (2014b) analysed five irrigation districts located in Cordoba and Seville, Southern Spain, using performance indicators, before and after modernization, stating that the average water savings were 23%, but the energy cost was increased by 149%, resulting in an average rise in the water cost of 52%. This increase in energy consumption has also increased the contribution of irrigation to climate change, as well as reducing its competitiveness due to associated costs.

Regarding the energy efficiency of these networks, traditional systems require almost no energy to distribute the water. Nonetheless, the energy dependency of pressurised irrigation networks has led to a percentage increase of the energy consumption of 657% in Spain from 1950 to 2007, supposing an increase from 206 kWh ha^{-1} to 1,560 kWh ha^{-1} (Corominas 2010). To this fact should be added the continuous increase of the energy cost, whose trend showed an increase of around 40% between 2014 and 2018 and the disappearance of the electricity special tariff for irrigation in 2008 (Red Eléctrica de España 2019a).

Hence, the energy dependency has arisen as one of the most dramatic issues within the irrigation. The cost related to the energy are usually included in the water costs. The analysis in the water cost of several networks before and after the modernization showed this bias. From one side, the energy dependency and the management, operation and maintenance (MOM) costs from €0.02 m^{-3} to around €0.10 m^{-3}, because of the energy demand increase, but also because of the associated costs to maintenance, exploitation and amortisation (Rodríguez-Díaz et al. 2008). In another research. Rodríguez Díaz et al. (2011) studied the weight represented by the water costs within the MOM costs after the modernization. The results showed how these oscillated between 0.04 – 0.18 € m^{-3}, contrasting the higher cost and energy requirements when the modernised infrastructures are compared with the traditional channels. Whereas the energy cost per unit volume supplied raised up to €0.04 m^{-3}, supposing 36.4% of the MOM costs. When the energy costs per unit irrigated area were analysed, the study concluded an increase from almost zero before the modernization to €103 ha^{-1} for pressurised networks.

Another effect noticed in other studies focused in Southern Spain was the trend to change the cropping pattern with the pressurised network and on-demand water availability. In Bembezar Margen Derecha irrigation district a dramatic decrease of the cotton was noted, moving from 24% of the irrigated area to 5%. On the other hand, citrus increased from 15 to 46%, occupying almost half of the irrigated area (Rodríguez-Díaz et al. 2011). Another research, which assessed this fact in four other districts, presented the same trend. Citrus suffered the highest increase in Bembezar Margen Izquierda and Guadalmellato irrigation districts, passing from 9 and 34% to 47 and 64% respectively. While cotton, which represented 13% in the first district, was completely removed and was reduced from 25 to 5% in the second (Fernández García et al. 2014b). The change of crops pattern, in which farmers look for more profitable crops to counteract the higher water costs is evident here.

Nevertheless, the consequences emerged from this energy dependency did not simply rebound in the water cost, but also in the volume applied. The analysis of the index known as Relative Irrigation Supply (RIS) demonstrates how the farmers' practises changed after the modernization. This index is defined as the ratio of the total annual volume of water diverted for irrigation and the volume of crop theoretical irrigation requirements. If the RIS value is over 1, it could be concluded that excess irrigation was occuring, whilst values lower than 1 show deficit irrigation (García-Vila et al. 2008). In the Bembezar Margen Derecha irrigation district, the RIS index varied from 1.36 before the modernization was carried out to 0.68, that shows deficit irrigation, in the post-modernization era, clearly showing a big difference in the amount of water employed (Rodríguez-Díaz et al. 2011).

Furthermore, the practice of deficit irrigation became prevalent as a result of the rising cost of water suffered due to the energy demand increase. When water costs are high, applying the optimum amount of water to obtain the maximum yield from a farm may not be the most economically advantageous approach. It is very usual in irrigation districts with high energy requirements not to use the whole amount of water assigned by the water authority, which may affect to the annual yield (Rodríguez-Díaz et al. 2004; Rodríguez Díaz et al. 2011).

Therefore, despite significant improvements in the water use efficiency, the pressurised systems have led to a dramatic increase of the energy demand, which caused some impacts in the farmers' exploitations. It could be stated that the modernization process of irrigation infrastructures steers the activity from a water to an energy efficiency issue. Hence, energy could be considered as one of the crucial factors for crops production in pressurised water networks, together with water availability and agro-climatic parameters (rainfall and evapotranspiration).

2.5. Measures studied to cushion the increase of energy demand

The aforementioned impacts brought on by on-demand pressurised systems arose the interest of researchers of the field to find solutions to counteract them. The investigations focused on improving the energy efficiency in irrigation covered measures related with the operation and management of the networks; rehabilitation of critical elements; or employment of renewable energies.

Among the solutions proposed within the irrigation network operation and management, they could be highlighted as irrigation sectoring, and the critical hydrant detection. Another solution studied within this field was the optimisation of the pumping station management using variable speed drives to adapt the manometric head to the network pressure requirements. Regarding the rehabilitation of irrigation networks, some studies were focused on how the energy demand could be decreased by redesigning the network employing optimisation algorithms. Lastly, the improvement of the energy efficiency was also studied using renewable energies.

These techniques are explained in detail below:

2.5.1. Irrigation Sectoring

As it was previously described, on-demand irrigation networks are designed to supply water constantly, water is continuously available to farmers, thus requiring enough pressure in all the hydrants fed. However, the orography, distance from the source or pipes diameter make the head requirements different for each hydrant. This fact is translated into an excess pressure in some hydrants, which should be dissipated for the irrigation devices to work properly.

The irrigation sectoring consists of grouping hydrants with similar head requirements. Thus, the head required at the source could be decreased to the value necessary to reach the most critical hydrant within each sector with at the service pressure, or minimum pressure needed to irrigate (see Figure 2-9). The hydrants with similar head requirements would form sectors that would operate independently by turns during some hours along the day. This technique has been studied several times for the last years, achieving significant energy savings. Furthermore, it has been applied together with some optimization algorithms, which allowed the minimisation of the energy consumption.

An investigation developed in an on-demand irrigation network located in Southern Spain analysed the energy decrease applying pressure dynamic regulation and sectoring. Energy savings of about 27% were estimated that could be achieved when the network was sectored, with 12 working hours per day and sector, and dynamic head at the pump station (Díaz et al. 2009).

A study carried out in central Spain compared four irrigation networks, two of which operated on-demand and the other two under rotation scheduling or sectoring. All of them had similar infrastructures (extraction station, reservoir and pumping station) but with different water sources. Therefore, the energy required for the extraction was not taken into account. It was concluded that energy efficiency could be improved, varying between 3.5 – 24.9%, showing a higher potential in sectored networks (Moreno et al. 2010a).

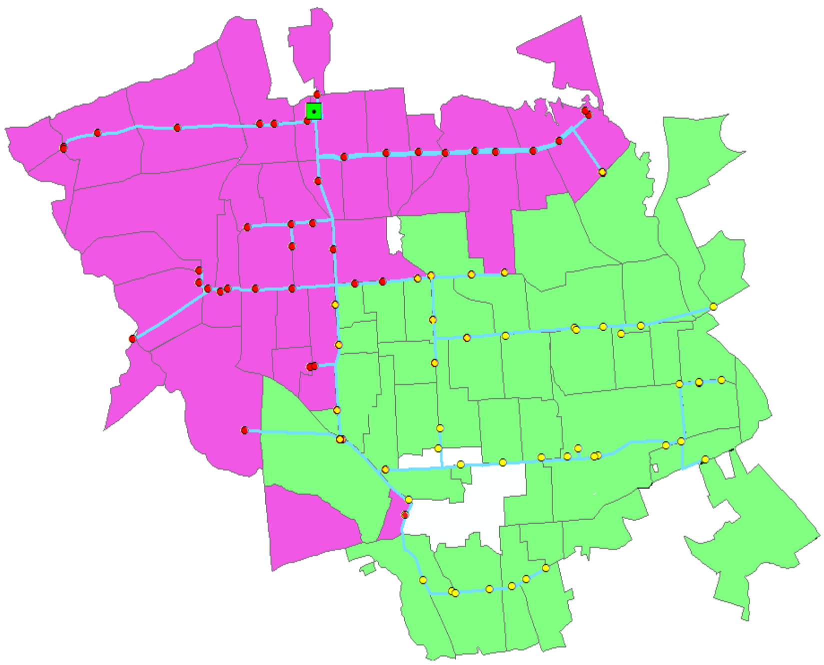

Figure 2-10. *Irrigation sectoring scheme with two sectors. Lower energy required at red hydrants and pink irrigated areas; Greater head required in yellow hydrants and green irrigated area.*

Another research carried out in an irrigation network in Eastern Spain, assessed the theoretical energy consumption decrease by using genetic algorithms and hydraulic models. The network irrigated a total area of 116 ha using 52 hydrants. The results of such a study showed important energy savings, decreasing by 36.4% in the best scenario (Jiménez-Bello et al. 2010).

Navarro Navajas et al. (2012) studied how irrigation sectoring improved the energy efficiency in a real case study of an olive grove network in Southern Spain. A modified version of the WEBSO algorithm (Water and Energy Based Sectoring Operation) (Cobo et al. 2011) was used. The research concluded that the energy consumption was reduced by almost 30%, increasing the farmers' profit in around 13%.

However while network sectoring can clearly save energy, a network with sectoring is no longer an on-demand network, which imposes limitations on users, as they would have water available during the irrigation turn.

2.5.2. Critical points detection

This method is based on the recognition of points (hydrants) with extraordinary energy requirements, which influence the pressure head required at the source. This can be caused due to the travel distance from the source, the elevation at which the point is located or undersizing of the network at those particular points (i.e. small diameter pipes, important head-losses). These points increase the total energy required by the network.

Several measures have been proposed and studied as potential solutions for these critical points, such as booster pumps installation or network rehabilitation changing the critical pipes' diameter, which led to significant energy savings in the main pumping stations.

Rodriguez Diaz et al. (2009) found 15 critical points in an on-demand irrigation network in Southern Spain, which were responsible for 15m of additional pressure at the main pumping station. Installing three boosting pumps at the three most critical points, it was estimated that an energy saving of 3MWh day^{-1} during the intensive irrigation period could be achieved.

Another research developed a General Energy Optimiser (GEO) to select the best strategy at the critical points to improve the energy efficiency in on-demand irrigation networks. It was applied in two irrigation networks in Southern Spain. The actions required to achieved in the first network implied the increase of the diameter in three pipes and installation of two booster stations; the first one with a fixed head of 20m and the second with a fixed head of 10m. The measures required at the second network needed the replacement of three pipes with different lengths for a greater diameter pipes. Energy reductions of 10.5% and 31.4% respectively, for a RIS = 1 were achieved (Rodriguez-Díaz et al. 2012).

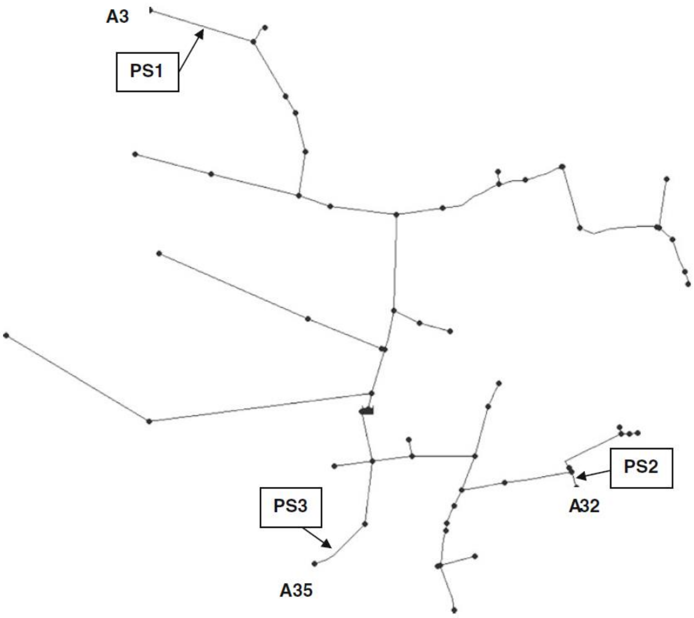

Figure 2-11. *Three critical points found at El Villar irrigation network, responsible of remarkable energy consumption and pipes to be replaced to improve its energy efficiency* (Rodriguez-Díaz et al. 2012).

Fernández García et al. (2016) employed multi-objective algorithms to optimise both, installation and operational costs while rehabilitating the irrigation network. The method was applied in an irrigation network. The redesign costs as well as the operation costs were analysed, selecting the optimal one in the long-term. Ten critical points were found, for which were proposed an increase of the diameter and calculated the optimal redesign cost. Besides, the most cost-effective operation schedule for the pump station in each stage of the irrigation season was also obtained.

The critical points detection was also tested in irrigation networks with multiple water supply points (pumping stations or reservoirs). The genetic algorithm NSGA-II was implemented in the Palos de la Frontera irrigation district to find the operation rule returning the lowest energy consumption in the set of a set of pumping stations when the critical points were disabled. The results showed 36% of energy savings when compared to the network operation. Moreover, this method achieved an additional 10% of energy savings when it was compared to irrigation sectoring (Fernandez Garcia et al., 2014c).

2.5.3. Improving the energy efficiency at pumping station

Another solution assessed was the improvement of energy efficiency at pumping stations, which are usually designed to supply water for the maximum demand period. For on-demand irrigation networks, the maximum demand coincides with the opening of all the hydrants simultaneously. Nonetheless, the likelihood for this high demands to occur is very small, provoking an inefficient operation at the pumping station during most of the irrigation season.

Using variable speed drives (VSDs) was proposed as a potential solution to fit the energy demanded at the pumping station to the energy required to supply water demanded at the irrigation network. Several studies analysed this measure, quantifying the energy savings that could be achieved.

Ait Kadi et al. (1998) studied how the application of variable speed pumps could influence in the energy consumption at the Massa irrigation scheme, located in Southern Morocco. The water demand records from 1991, 1992 and 1993 irrigation seasons showed that the pumping station discharge did not exceed 66% of the maximum design value. The energy savings were estimated at around 16%, reaching values close to 18% when sprinklers were replaced by drippers.

Another research carried out in Southern Italy evaluated how the implementation of variable speed drives could affect the energy consumption of the pumping station in two irrigation networks. The results showed that energy savings of 27% and 35% could be achieved respectively (Lamaddalena and Khila 2012).

Fernández García et al. (2014a) developed a new model (WEBSOMPE) to optimise the irrigation sectoring and the manometric head at the pumping station using various VSDs. The different results obtained as per the number of VSDs considered can be seen in Figure 2-11. The best scenario indicated an energy saving of 26% annually, using three VSDs and three sectors in the Bembezar Margen Izquierda irrigation district.

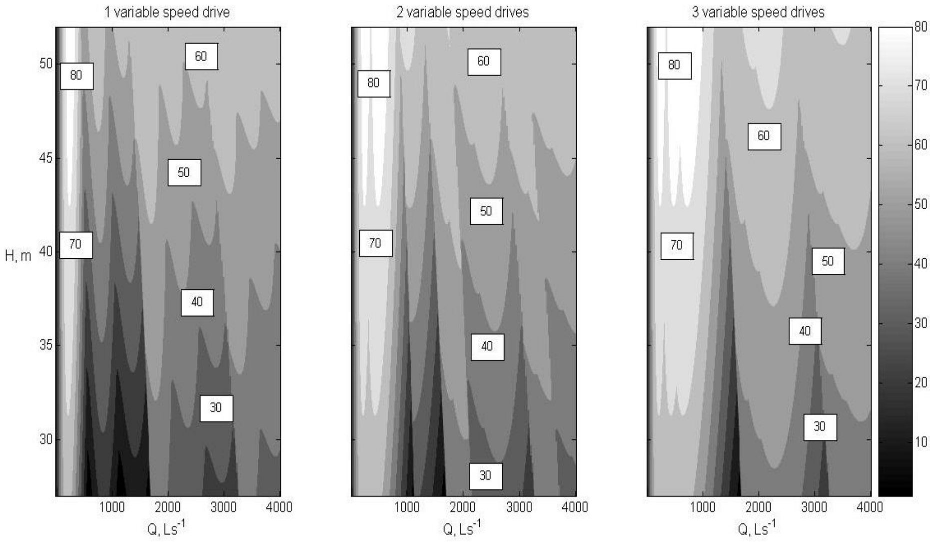

Figure 2-12. *Pumping station efficiency depending on the variable speed drives considered* (Fernández García et al. 2014a).

2.5.4. Renewable Energies

Previous measures were aimed to improve the energy efficiency by decreasing the energy consumption of irrigation networks. However, they did not suppose any change of the energy sources used to supply the energy demanded. Renewable energies relevance became significantly important during the last years, thus being the core of numerous investigations carried out during in order to replace fossil sources. The different studies developed proposed various approaches in different scales using solutions such as: photovoltaic for solar pumping; hybrid solutions using solar and wind energy to satisfy the energy requirements; smart networks fed with solar energy; incorporating hydropower; etc. A review of these studies is presented below:

Hamidat et al. (2003) evaluated the viability of installing two solar plants to feed two pumping stations in Algerian Sahara to irrigate small plots of about 2 ha. The crops cultivated, together with the climatic conditions of the area, and the solar radiation recorded indicated the suitability of this solution in Saharan regions with low water head.

Another research compared the performance and economic viability of diesel pumps to photovoltaic (PV) pumps for small irrigation schemes. In a life span of ten years, the solar pump was estimated to be around 64% of the cost of diesel pump. Furthermore, the potential of this technology in India was estimated as a volume oscillating between 9 and 70 million solar pumping sets, which would be able to avoid a diesel consumption of around 255 billion litres annually (V and S 2015).

Regarding the hybrid solutions, Vick (2010) studied how wind-solar systems could be implemented in the Great Plains (US). The author concluded that to make this solution could be cost-effective in large irrigation schemes when the crops cultivated were divided into winter and summer crops rather than being focused in one of them.

One of the latest solutions assessed consisted of smart irrigation management systems using solar pumping. In this research, the Smart Photovoltaic Irrigation Manager (SPIM) model was developed. The SPIM was defined as a real-time model able to couple the PV power available, depending on the solar radiation, with the energy required to fulfil the irrigation requirements of the different sectors. In order to avoid the use of diesel pumps in those days with lack of PV power, the irrigation water requirements were fulfilled either using the soil water stored or over-irrigating in the following days. The model was applied in a 13.4 ha experimental farm divided in three sectors, located in Southern Spain, where a 15.4 kW system of peak power was installed to feed a 13 kW submersible pump. The irrigation water requirements were fulfilled during the entire irrigation season, saving 100% of the energy previously consumed by the system and avoiding 1.2 t eCO_2 emissions (Mérida García et al. 2018). Some large solar pumping systems for irrigation in part of a conventional irrigation district is being implemented, supplying energy to some of the pumps installed and selling energy to the grid when there is no consumption. However, the farmers generally require energy while they are irrigating, as it is needed for the practise (i.e. fertigation), which not always coincides with the light time when the solar panels would generate power.

The numerous measures explained in this section aimed to improve the energy efficiency in irrigation networks, either reducing the energy consumed by modifying the irrigation management or pumping station or by replacing the energy source feeding the network. Nonetheless, the largest renewable energy producer was not taken into account yet. The application of hydropower to improve the energy efficiency in irrigation networks is the core of this thesis, therefore we first discussed the concept, application in water networks and challenges faced in irrigation. A first approach to micro-hydropower and its application in urban water networks (drinking and wastewater) is given below, where this technology has been more studied.

2.6. Hydropower

Hydropower is the energy obtained from flowing water, taking advantage of its existing potential or kinetic energy. This energy was already exploited by the ancient Greek civilisation, using water wheels to grind grains. The technology has been developed along the years, becoming the largest renewable energy source nowadays accounting for around 1307 GW installed capacity. Furthermore, the capacity is forecasted to be increased by 9% in the next five years (IEA 2019).

Hydropower can be divided into six different categories depending on the power output of the installation:

Table 2-2. *Hydropower classification depending on the power production*

Hydropower category	Power range
Pico – Hydro	0 kW – 5 kW
Micro – Hydro	5 kW – 100 kW
Small – Hydro	100 kW – 1 MW
Mini – Hydro	1 MW – 10 MW
Medium – Hydro	10 MW- 100 MW
Large - Hydro	100 MW+

There are many existing dams across the world, which do not have installed hydropower plants for electricity generation. The largest environmental impact associated with conventional hydropower lies in the construction of a dam and the related changes to the local eco-system. The IPCC report on hydropower reports that only 25% of the world's large dams contain a hydropower turbine (IPPC 2011). According to Lehner et al. (2011) this unexploited potential in existing large dams could raise to over the 900GWh per year, including non-EU European countries.

However, projects encompassing power between large and mini hydro have been limited due to the environmental pressure and the impacts related to their construction and power generation. Although the scale of the impacts will vary as per the plant location, hydropower has been traditionally associated with dams, where the formation of reservoirs has caused dramatic effects on the autochthonous flora and fauna and their habitat. Nonetheless, it must be borne in mind that the construction of dams has helped to storage water in arid and semi-arid regions, making it available during dry periods, and avoid other catastrophe, such as floods.

Therefore, the latest research on the field of hydropower have been orientated to investigate and assess the existing resources on pico, micro and small hydro generation and the technology to be applied in sites with minimal environmental impacts. Within these sites, different existing hydraulic infrastructures could be found, such as: water supply networks (WSN), wastewater network or irrigation channels.

Hydropower generation in WSNs has been the aim of a diverse range of studies in the last decades. Various authors highlighted the potential for energy recovery using micro-hydropower (MHP) turbines at points of excess pressure. Dating back to 1996, Wallace (1996) enhanced the need of reducing the existing potential energy in piped water networks before the treatment process, that could be translated in an output energy recovery ranging between 10 and 1000 kW. In addition, other places mentioned by Wallace where this solution could be adopted, referred to intermediate storage reservoirs, filtration processes where it is required to break all the pressure, break pressure tanks, colander valves or pressure reducing valves. Nonetheless, the energy potential was not quantified in this study, but MHP was proposed as a solution for energy recovery.

Gaius-obaseki et al. (2010) presented an overview of the potential locations within water and wastewater networks for hydropower application. It was stated that hydropower could be exploited at the outlet of wastewater treatment plants, diverting the treated sewage and turbining it before discharging into the water body. The author also stated that turbines could be installed into wastewater treatment process flows instead, previously evaluating the blocking likelihood of the turbine and network. An output power of about 19kW could be obtained if the turbine would be installed at the exit of the tertiary sand filter, where a head of around 6m exists in most of the cases. The main disadvantage found at the wastewater treatment plant is the low head available, which increases the risk of the investment and makes many of the installations unviable. Regarding the WSNs, pressure reducing valves (PRVs) or break pressure tanks (BPTs) appeared as an opportunity for hydropower applications. As the energy is dissipated in both cases, previous literature proposed the use of turbines to recover that energy. In the case of PRVs, either the installation of inline turbines replacing them or turbines in parallel to the PRVs were proposed.

McNabola et al. (2014a) extoled MHP as a technically feasible technology to decrease the energy dependency and its impacts of water industry in urban networks. The study presented a review of the energy use to extract, produce, distribute and treat water and CO_2 associated to these activities. Due to the high energy consumption (2-3% globally, 30-60% at city level, 0.8 kWh m^{-3}) and the dramatic economic and environmental impacts (5m t CO_2 per year in the UK, €600 million per year in Ireland) reported in previous literature (Environmental Agency 2009; Kwok et al. 2010; Li et al. 2010; Venkatesh and Brattebø 2011; Zilberman et al. 2008), McNabola et al.

(McNabola et al. 2014a) highlighted the existing energy recovery potential in the water industry and presented the challenges to be faced for MHP application. The location proposed encompassed PRVs, BPTs, storage reservoirs and wastewater treatment plants. Different results from previous studies carried out in each of the locations were shown. Nonetheless, the author outlined the challenges to be faced in future research in order to have a feasible quantification of the energy recovery potential and cost-effective solutions. One of the main challenges related to the energy estimation was the flow fluctuations. Thereby, many of the previous analysis used average data, not considering the performance variability of turbines, hence over or underestimating the energy recovery potential.

Nevertheless, a major barrier that restricts the application of turbines in many cases is the cost of traditional turbines with small power outputs are not economically viable, requiring of more cost-effective turbines in order to make this solution a reality.

One of the first approaches of MHP in water networks, coming up with cost-effective and small power output turbine was carried out by Williams et al. (1996, 1995; 1998). Pumps as turbines (PATs) were proposed to be installed in parallel to PRVs, thus recovering part of the energy dissipated. The practical application for such solution was developed in 1998 (Williams et al. 1998) installing a PAT at a water treatment plant at Blackpoll, parallel to an existing PRV. Conclusions showed that energy could be recovered, but further research should be conducted in order to improve the predictions of the conditions, and hence the performance.

Since then, many investigations have studied the use of PATs in piped water networks. These studies dealt with the different issues, encompassing topics that varied from, where the turbines should be installed within a network to optimise a pre-set variable, anticipate the PAT performance using different computational techniques or summarising different strategies for which this kind of installations could be constructed. In the next sections, different works focused on the application of hydropower in urban and irrigation water networks and PATs properties, threats and strengths, are discussed.

2.7. Pump-as-Turbine technology

PATs are conventional pumps working in reverse as turbines. Using them for energy recovery has been shown to be cost-effective at sites with small power output capacity rather than conventional turbines. Their cost-effectiveness lies in the fact that pumps are mass produced and many models exist of differing sizes. This results in considerable cheaper machinery covering a wide range of flow and head combinations. The cost competitiveness over traditional turbines extends from 1-2kw to 50-100kW. However, anticipating their performance is a well-known challenge.

Ramos et al. (2009) compared conventional turbines with low cost solutions for MHP schemes. It was shown how the initial investment difference between both solutions increases as the nominal power decreases. The author stated that PATs installed in water networks with a payback period of six years would be economically viable for power outputs greater than 10kW, concluding that increasing the initial investment, the power output and profits could be also increased, hence reducing the investment return.

Power et al. (2014) developed a methodology to assess the energy recovery potential in wastewater treatment plants considering conventional hydro turbines and PATs. The cost difference found between both technologies was discussed, stating that the cost of PATs was hanging around five times less than traditional turbines.

Motwani et al. (2013) carried out a cost analysis which compared the viability of a pico hydropower plant of 3kW using a PAT, and comparing the results with a theoretical Francis turbine. Despite of a lower peak efficiency and relative performance of the second option (60% maximum against 80% for the Francis), the annual life cycle cost justified the potential installation of a PAT rather than using the Francis turbine. Based on previous reference, the author highlighted the significant differences on the cost of both technologies, stating that the installation of a PAT could lead to an investment reduction of the order of 90%. The results of the research showed how the cost of the Francis turbine for the proposed installation could suppose up to eight times more than the PAT.

Novara et al. (2019) developed a cost model able to quantify the electromechanical devices (pump + generator) cost based on the BEP. The model proposed four cost equations, using generator of two, four or six magnetic poles with radial pumps. A database of 343 pumps and 286 generators were used. The equation used were single linear regressions.

Nonetheless, as stated before, PATs have the disadvantage of relatively low efficiency, which can reduce further with large flow fluctuations. It has been shown that efficiency of the PAT can reduce to approximately 70% of the maximum efficiency when the flow was 20% below the Best Efficiency Point (BEP) flow rate (see Figure 2-13) (Lydon et al. 2017a). This important efficiency variance is due to the lack of control mechanisms, which exist in conventional turbines. In order to avoid an over or undersize of the plant when using PATs, the conditions of variability have to be thoroughly studied. A bad design and power selection of a PAT for a specific site can lead to higher returning periods of the investment, which sometimes could turn the installation not economically viable. This fact together with the anticipation of the PAT performance increases the complexity and risk when designing this kind of installations.

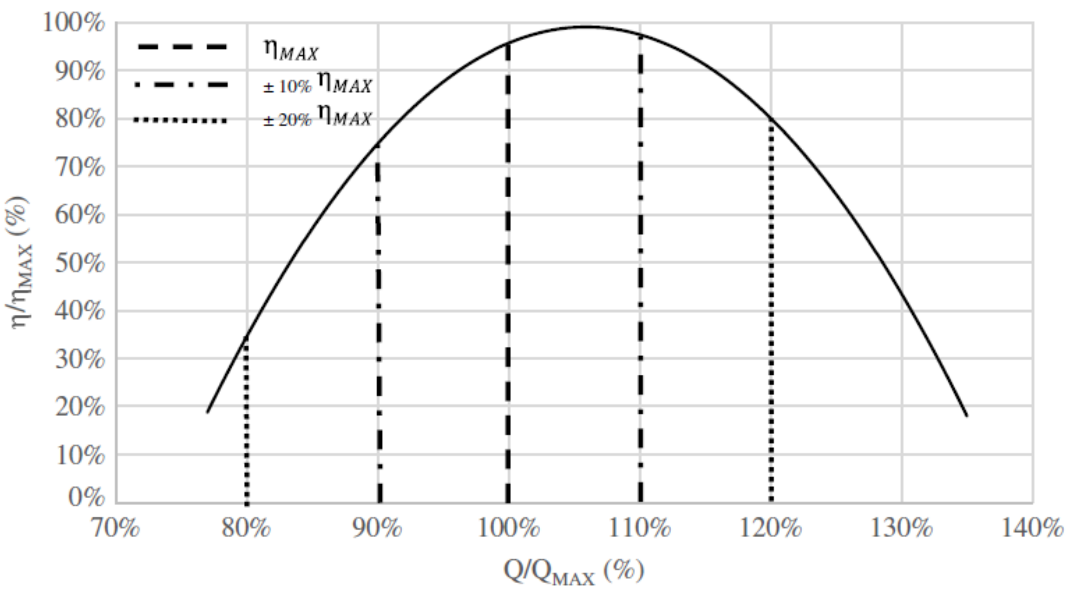

Figure 2-13. *PAT relative variation efficiency depending on the flow rate* (Lydon et al. 2017a)

Another difficulty found when this solution was assessed to be applied in WSNs was the location to be installed. As previously stated, PATs were proposed to be installed in parallel to existing PRVs or even to replace them. However, PRVs locations are not selected to maximise the energy production, but they are installed in strategic points to decrease the pressure down to values close to the required.

In order to control the hydraulic working conditions of the PAT, two main schemes were primarily proposed: i) Hydraulic regulation (HR), in which the flow and head of the system are controlled by hydraulic devices (valves); ii) Electric regulation (ER), in which the rotational speed of the PAT is adjusted depending on the available conditions at the network. Carravetta et al. (2014a) carried out a comparison between both schemes, concluding that HR performed better for low backpressures. However, a door was let open to explore the possibility of aggregating both schemes in a hybrid one, which was defined as promising by the author.

One of the greatest challenges that researchers faced in the last years was to anticipate the PAT performance. This is required to foresee the energy recovery potential based on a flow variability, and is core of every feasibility study before the construction of a plant. The main reason why the PAT performance variation as per the flowrate is unknown is because of the lack of curves provided by the manufacturers. Pump manufacturers might not be interested at the moment on testing pumps working in reverse as there is not a big market for its application on real world. Therefore, large-scale impacts of the technology within the water industry should be carried out to thus assess not just the potential benefits, but the economic market as well. This lack of actual information has led to different approaches and methods to face this challenge, providing different but quite interesting results. Considering the working point of a PAT is unknown at the start of the design process, that there is considerable errors in the conversion methods, and that the PAT has poor part-load efficiency, these factors combine to make the use of PATs complex and high risk for designers.

Barbarelli et al. (2016) presented a one-dimensional numerical model, which could be divided in two stages to convert from pump to PAT. During the first part of the calculation, the model calculated the geometric properties of the PAT. On the second, the losses were estimated and the characteristic curve of the PAT defined, obtaining errors ranging 5-20%. As input requirements to estimate the geometry of the device, the author defined six parameters: Flow (Q) and head (H) at the BEP of the pump, maximum power, head at the shut off, impeller diameter and size of the pump, generally available on the manufacturers' catalogues.

One of the first research works on the prediction of PAT performance proposed comprised two equations to obtain the characteristic curves of centrifugal pumps working as PATs, in study developed by Derakhshan and Nourbakhsh (2008). The equations were formulated based on a set of centrifugal pumps, which were experimentally tested as turbines, obtaining the relationship among the head and the flow at BEP, and the power and the flow at BEP. Thus, Derakhshan proposed a simple way to calculate the power and head curves, very useful in preliminary stages of MHP, where manufacturers usually never provide this information.

Fecarotta et al. (2016) opted to use classic affinity law and the Sutter model to obtain the characteristic and efficiency curves. To understand how it works, it could be helpful to know that two pumps of the same type can be considered similar if they have the same specific speed. Hence, the properties at BEP of a prototype was related to the BEP properties of a similar pump requiring the diameter of the impeller and the rotational speed for both. The study used five PATs working at different velocities, obtaining their characteristic and efficiency curves, which were compared to the curves estimated by using the model described.

Huang et al. (2017) introduced a new method to estimate the characteristic PAT curve known as the rotor-volute matching principle. Deriving the theoretical formula of rotor characteristic, the equation obtained could be used to obtained the flow and head at BEP for a given PAT. The author stated that the impeller, rotor and volute had an important weight on the hydraulic performance. The BEP of the device working as pump and as turbine could be obtained matching the characteristics of the impeller and the rotor for the first case and matching the characteristics of the volute and the rotor for turbine mode.

One of the latest works to anticipate the PAT performance used computational deep learning techniques for such purposes. Artificial Neural Networks (ANNs) were proposed by Rossi and Renzi et al. (2018) to foresee PATs' characteristic curves and BEP. The model required the operating points in pump mode as input, returning the operating points of the device working in turbine mode for a specific device. The model accuracy was tested, showing maximum errors of ±5% and ±1.85% for the BEP and characteristic curve respectively, when the experimental and predicted data were compared.

Another technique used in previous research for the purpose discussed has been the application of computational fluid dynamics (CFD). Rossi et al. (2019) developed a numerical model using CFD capable to predict the performance curve of a given PAT inputting a few parameters related to the BEP, such as flow and head coefficients, specific speed and power coefficient. The model predicted the performance curve with an error of ±7%.

Barbarelli et al. (2017) tested 12 pumps working in natural operation and in reverse mode. Heads and conversion factors were defined from this test between both modes. As result of this research, Barbarelli proposed a quadratic equation, which allowed the characterisation of any PAT defining its BEP.

Comparing the different methods proposed in the existing literature, the weaknesses found for each of them are discussed. CFD requires of the building of models for each case, as the different characteristics of the devices might change (i.e. diameter of the impeller). This fact turns impractical the CFD methods for designing PAT installations for energy recovery, as pumps are product standardised and can be found easily in the market. Moreover, the method proposed by Rossi et al. (2019) did not suppose an improvement with respect to other simpler methods based on quadratic equations. Other methods as the rotor-volute (Huang et al., 2017) or the geometrical model proposed by Barbarelli et al. (2016) are impractical as they required of much data generally not provided by the manufacturers, such as dimension of the impeller, dimension of the volute, number of blades, etc. The affinity law requires of at least one characteristic curve to estimate the behaviour of other PATs. During the design phase, it might be difficult to obtain this information, as manufacturers keep this information for the selling stage. Thus, methods proposing quadratic equations obtained from the extrapolation of different curves were concluded to be the one with the higher scope of application, in addition of greater simplicity for their application. The equation proposed by Barbarelli et al. (2017) was selected in this thesis to obtain the PATs characteristic curves, due to the good fit obtained by the author ($R^2 \approx 0.93$). In addition, as many theoretical PATs were evaluated in this thesis, this method resulted the best to be applied, as it just required of the BEP to estimate the characteristic curves.

Novara et al. (2018) used a larger dataset of PAT characteristic and efficiency curves to develop a polynomial model to estimate the characteristic curve of any PAT. Based on data of 113 PATs, the model required of given parameters prior to obtain the curves, such as BEP, rotational speed or specific speed. The efficiency was also cautiously assessed, highlighting the risk of a bad design plant, which could lead to very low global efficiency issues. Following the previous considerations for the characteristic curve, the efficiency behaviour proposed by Novara et al. (2018) was used in this thesis to characterise the plant efficiency depending on the flowrate, as it was the method based on the largest PATs database, as it could be estimated as per a quadratic equation based on the BEP.

Based on all the previous research about PAT, a SWOT matrix has been developed, showing the most important points found within each of the fields (**S**trengths, **W**eaknesses, **O**pportunities, **T**hreats) (Figure 2-14).

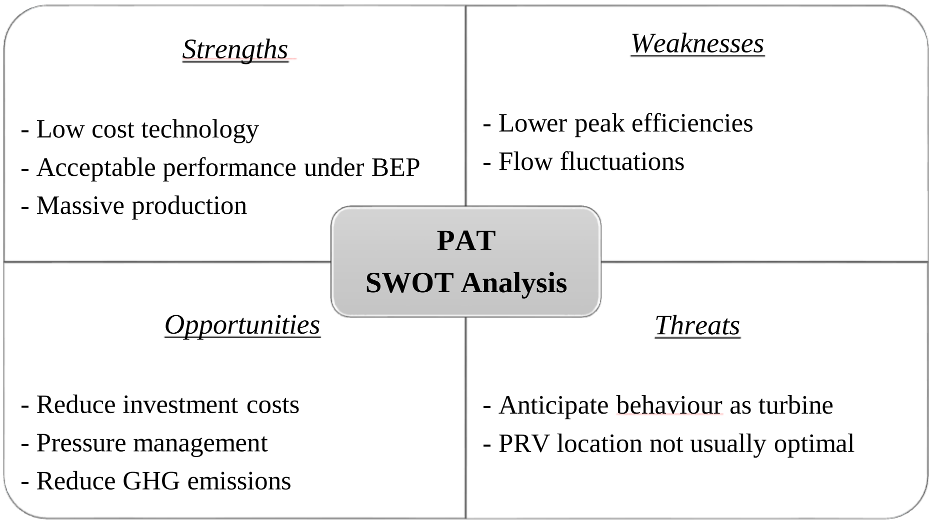

Figure 2-14. *PAT SWOT matrix*

Strength

PATs have been reported as a cost-effective solution for energy recovery in water networks. Numerous authors stated that PATs could be for about 1/10 of the cost of small-scale conventional hydro turbines for small power outputs (Ramos et al., 2009; Carravetta et al., 2014; Fecarotta et al., 2015; Lydon et al., 2017; Novara et al., 2019). The fact turning PATs in a cost-effective technology is the massive production of traditional water pumps. This makes easier the search of a turbine for any point required. While conventional turbines are usually manufactured under order for a particular site, PATs can be ordinarily found in the market. Furthermore, this technology was found to have an acceptable performance under best efficiency conditions, reaching peak global efficiencies over 70% (Caravetta et al., 2013; Novara et al., 2018).

Weaknesses:

Although PATs could have a high peak efficiency, it dramatically drops when the flow fluctuates from the best efficiency point. This has been proved in numerous studies. Lydon et al. (2017a) analysed the behaviour of the efficiency when the flow rate changed, concluding that the PAT efficiency was reduced by 22% and 70% at flow conditions of ±10% BEP and ±20% BEP respectively, and dropped off completely at flow conditions of ±50% BEP. To solve this efficiency drop, Carravetta et al. (2013) proposed the regulation of the operating conditions at the PAT, by either using hydraulic (control valves; Hydraulic Regulation) or electric devices (variable speed drives; Electric Regulation).

Opportunities:

The adoption of PATs for MHP solutions might provide a number of opportunities to enhance its application. The cost-effectiveness presented in the strengths would reduce the investment costs required build this kind of systems. The construction of MHP plants would suppose a new renewable energy resource, which would help to reduce the GHG emissions related to the water industry. Furthermore, PATs have been proposed as potential solution for pressure management in WSNs, which sought the leakages reduction through the pressure regulation (Fecarotta et al., 2017).

Threats:

PATs present some difficulties when anticipating its behaviour as turbines. Divers methods, discussed previously in this section, have been proposed for this task. However, all the methods presented some advantages and disadvantages. Thus, to anticipate the PAT behaviour is still one of the challenge to be solved to foster this technology in the water industry.

Another threat found during the literature review was that the location of the PRVs in WSNs usually do not coincide with the optimal points to maximise the energy recovery or minimise the leakage. The option of installing PATs in parallel to PRVs could be fostered within water schemes, assessing the optimal locations for such purposes before installing the PRVs. This would lead to a reduction of the operational cost.

2.8. Hydropower in urban water networks

Water networks are commonly sub-optimal in terms of their use of energy and water resources, because of changes in elevation, demand, water-pressure and leakage rates across many kilometres of pipelines. Recent research has studied the application of MHP turbines in drinking water supply and wastewater infrastructure to reduce pressure to desired levels and recover energy in the form of electricity.

Independent of the technology proposed, many studies have been developed on hydropower in water networks during the last years. A critical overview of some of them is shown below, presenting the different approaches used and locations within the water supply and wastewater networks.

McNabola et al. (2014) presented the opportunity of energy recovery at BPTs, assessing the existing potential on 10 tanks distributed around Ireland. Although initially just three of the BPTs evaluated presented economic viability, most of them turned viable when UK feed-in tariff was applied instead. Significant economic and environmental savings could be achieved by adopting MHP in these locations.

Corcoran et al. (2013) carried out an analysis of the existing MHP potential using data coming from PRVs, BPTs and reservoirs distributed around Ireland and the UK. A total of 95 sites were assessed, accounting for an existing potential greater than 600kW. However, the diversity of the data used increased the uncertainty of the results presented, since for some of sites the data corresponded to 15 min records during a whole year, and for other average flows and heads were used. Different type of turbines were evaluated, all of them within the catalogue of conventional turbines. For those sites with actual data recorded, the variation of the efficiency of the turbine was considered, whilst average efficiency was considered for the sites with average values. This last fact could lead to overestimation of the existing potential, as it was stated previously.

Power et al. (2014) evaluated the potential at more than 100 wastewater treatment plants, gathering data from plant of Ireland and the UK, from which just 25 were found to be economically viable. The main barrier found in wastewater treatment plant to have such a small ratio of viable MHP sites is the small head available. However, the power found for the viable sites was over 1 MW. The emission savings were estimated in more than 1,000 teCO_2. It could be extracted from the research how population associated to a wastewater treatment plant affected to the viability of MHP solutions in this infrastructure, as the head available is too low and it would require large flow values to have enough power potential.

Gallagher et al. (2015) estimated an annual energy recovery potential of 20.1 GWh in 238 sites in water and wastewater networks in Ireland and the UK, which would be capable of supplying energy to 4,702 households in Ireland and Wales. Notwithstanding the great potential found, the author highlighted the need of more cost-effective solutions, rather than conventional turbines, as many of the sites analysed showed low power potential, which would turn into a non-consideration of this solution.

Carravetta et al. (2012) defined a PATs design methodology for energy recovery in pressurised networks. This method presented was known as Variable Operating Strategy (VOS), which aimed to maximise the energy production in the variable working conditions of a hydropower plant within a water network. One of the main novelties found in this work was the consideration of seasonal variations of the variables present at the network, which would directly affect the plant efficiency and provided a more realistic approach for the potential assessment. This was achieved considering the interaction among the PAT characteristic curve and the available flow and head at the network in each case, defining the domain of the flows and heads to be diverted and turbined. This can be seen and understood more clearly in Figure 2-15, taken from the referenced work.

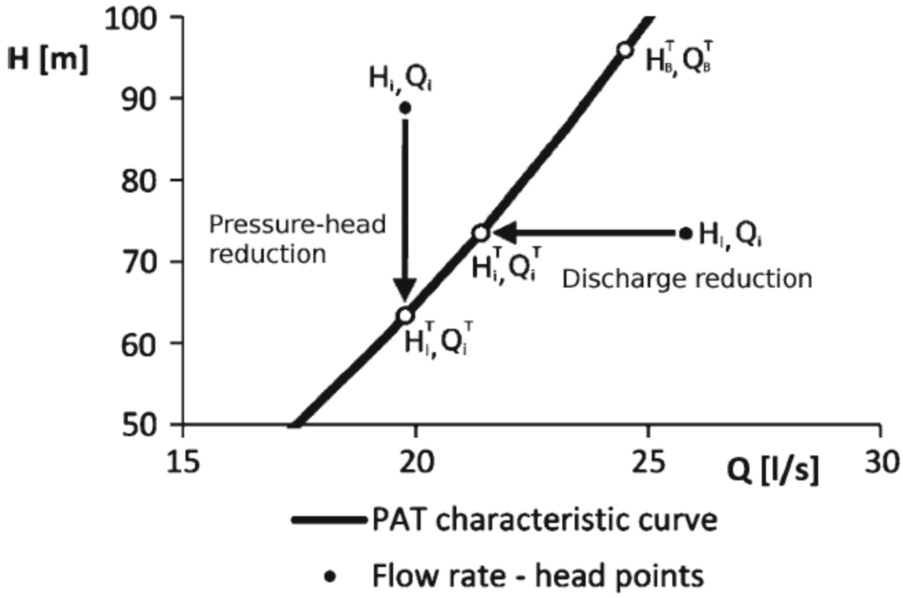

Figure 2-15. *Operation scheme of the Variable Operating Strategy* (Carravetta et al. 2012).

Lydon et al. (2017b) evaluated the application of PATs for energy recovery and pressure control in three PRVs of the Dublin water network. For such purpose, a lab-scale prototype PAT was characterised. Using the affinity law and Sutter model mentioned at the previous section, the performance of PAT to install in each of the sites was obtained. The energy recovery potential using the predicted characteristic curves and performances, were then assessed inputting high-definition flow and upstream and downstream head readings data, recorded every 15min for one year long (2013). The results showed that 40% of the potential energy dissipated by the PRVs could be converted into electricity. Moreover, it was highlighted that the use of two PATs in parallel would increase the global efficiency of the system. This scheme is typically recommended in those sites with high flow fluctuations, installing one PAT with a smaller power output and one with a greater power. In this way, the flow would be diverted to either one of the bypasses or to both, depending on the value.

2.9. Hydropower in pressurised irrigation networks

Besides the solutions studied by other researchers to decrease the energy dependency in pressurised on-demand irrigation networks, which were discussed in previous sections, MHP could be introduced as an attractive solution for such purpose. A significant body of research has been conducted on this MHP in recent years for drinking water networks; however, very limited attention has been given to its application in the irrigation sector, each of them presenting different approaches. Despite the aforementioned challenges, a few authors have studied the application of PATs for energy recovery in irrigation networks, proposing different assessment and design approaches.

Tarragó (2015) assessed the potential energy that could be recovered annually in the Alqueva irrigation district (Portugal). A division was made by the author between irrigation channels and pressurised systems. For the second one, the core of this thesis, annual mean flow and available head were used to estimate the power potential using PATs for an irrigated area of 68 ha. The nominal power proposed raised up to 0.24 kW, producing 2.1 MWh per year. This approach did not consider the flow fluctuations within the network, which could suppose an under/overestimation of the MHP potential. The method also only considered power potential within the network and not at farm-level.

Pérez-Sánchez et al. (2016) used historical data records to quantify maximum potential energy recovery, where flow and head fluctuations were considered when the power production was calculated. A maximum annual potential energy recovery of 188.23 MWh was estimated to be achieved at all the consumption points in an area of 290.2 ha, that would avoid an amount varying between 137.4 t eCO_2 and 216.2 t eCO_2 yearly, depending if coal or gas was considered. However, PAT performance was considered constant regardless of the flow rate.

Another investigation studied optimization strategies to maximise the energy recovery using PATs considering different objectives function (Pérez-Sánchez et al. 2017). For such purpose, the main properties of the devices had to be defined (i.e. specific speed, rotational speed, impeller diameter). Different experimental curves were obtained, from which the characteristic and head curves were obtained depending on the flowrate. The method returned a yearly energy recovery potential of 58.18 MWh in an irrigation district of 290.2 ha. Nevertheless, economic feasibility was not included. This a critical variable when considering PAT installation in irrigation networks for energy recovery.

Perez Sanchez et al. (2018) developed an innovative methodology to select PATs for energy recovery at irrigation networks using simulated annealing techniques. The method sought to maximise the energy recovery, selecting actual devices from which the curves were known. To test the service conditions at the network, the PATs were simulated, confirming that no impacts on pressure limits would be suffered after their installation. A maximum energy recovery potential of 26.51 MWh was estimated, which supposed an annual energy saving of 10% at a 290.2 ha irrigation district. The method used a limited number of curves, excluding other that may be available at the market, which could suit better to the points analysed.

García Morillo et al. (2018) studied the energy recovery potential in an irrigation network using average and most likely predicted flows and heads, assuming constant efficiency as well. Four points showing excess pressure were analysed, for which different hydropower solutions were assessed. The author proposed one Francis turbine and three PATs for the points studied, able to recover 270.5 MWh per year and avoid 108 t eCO_2 annually. Nonetheless, the facts previously commented (no flows nor efficiency variations) could lead to overestimation of the existing potential.

These investigations, which applied very interesting techniques, supposed a first approach to the consideration of MHP generally and PAT particularly, as a potential solution to decrease the energy dependency of irrigation networks. However, it was found that some important analyses or considerations were missing in each of them, which could influence into the feasibility of this technology, making it as not suitable for application at these systems.

The flow fluctuations at irrigation networks tend to be considerably more pronounced than in WSNs, since the demand will depend on the irrigation requirements of the crops cultivated and the yearly climatic parameters, such as rainfall and potential evapotranspiration. The water demand is also concentrated in just a few months of the year in certain cases, meaning the economic viability must be achieved from flows occurring across typically 5-6 months of the year. These considerations directly affect to the plant efficiency variation, as it was presented in the previous sections. Although a detailed control of the volume consumed is carried out in order to set the energy tariff to each farmer, the limited existence of high-definition data recording devices (i.e. flow meters recording hourly flows) turn the assessment and the device selection into a complex challenge.

Moreover, the consideration of a limited number of actual characteristic and performance PAT curves limit the potential employment of actual PATs whose BEPs suits better for a specific case. Since manufacturer are usually reluctant to share this information or simply do not possess it, theoretical curves should be used at this stage, hence defining the theoretical BEP that fits the best for each actual particular site. This BEP could be shared afterwards to different manufacturers, getting actual PAT curves whose BEPs are the closest to the theoretical one, if not the same. In addition, considering constant efficiency would lead to an overestimation of the energy recovery potential, as large flow fluctuations would considerably reduce the plant efficiency.

Although some limitations have been shown at the literature, it has been highlighted that hydropower energy recovery is possible within pressurised irrigation networks. PATs have been also remarked as cost-effective devices to be used in micro hydro scale solutions, showing a good performance if the working conditions are controlled. To prove the feasibility of this technology, actual scale pilots should be constructed and tested, which would also incentivize the adoption of PATs at these locations. Significant economic, energetic and environmental savings could be achieved implementing MHP in irrigation sector, at both, water distribution and farms, where usually there is no grid connection due to the large areas covered by the network and energy is required for the irrigating for different devices (i.e. filters or electric fertilizers).

2.10. Summary

Pressurised irrigation techniques are gaining weight continuously worldwide, since they are leading to important water savings in the largest water consuming activity on the planet. Furthermore, this fact is even more important in semi-arid and arid regions, where the water scarcity is an actual threat for irrigation. Therefore, this has carried to a replacement of the irrigation infrastructure in some areas, characterised by the replacement of traditional open channel or mills for pressurised pipe networks. A direct consequence of this change is the increase of energy consumption, required to either boost the water to a reservoir or raise the manometric pressure to reach every water consumption point of a network.

This fact has caused some effects on the irrigation activity, such as the increase of the water costs or the emissions associated to the energy consumption, previously avoided. To counteract these effects, different solutions were proposed and assessed. Some of them were related to the irrigation network management and showed how the energy consumption could be reduced by sectoring the irrigation or replacing some elements on the network, which had been undersized during the design phase. Renewable energies were also studied as a potential solution to decrease the energy dependency of pressurised irrigation networks. Solar energy was successfully applied in an experimental farm feeding a pump station, avoiding any extra energy consumption. Moreover, it is also becoming a real solution adopted for big pumping station in large irrigation communities, where part of the pumps might be feed with the electricity produced by the solar panels. Nevertheless, this solution showed a use limitation: it can only work during the daytime. While in large irrigation networks there are periods of night time irrigation.

Hydropower has been proposed as a viable solution capable of reducing the energy dependency and bring electricity to remote places with energy requirements, such as farms. However, some effects present in irrigation required a deeper research in order to improve their selection and design. The large flow variability in on-demand pressurised irrigation networks is a real threat for PATs application. Theoretical and experimental works are needed in order to check the feasibility of the technology in the field, as well as define the procedure and different stages along a MHP project life span.

This research will investigate the different issues found at the previous literature, being focused on the characterisation of the flow variability, the feasibility of flow prediction methods, quantification of MHP energy recovery potential and the design and analysis of an actual scale PAT installation.

3 RESEARCH APPROACH

To achieve the aim and objectives proposed and address the questions formulated, this research incorporates a combination of experimental work, economic and environmental analysis and fieldwork.

3.1. Research Model

The stages in which the research was divided coincided with the different prerequisites needed to quantify the potential hydropower and the scale in which was carried out. Hence, three main stages can be found: a desk work period, in which all the theoretical requirements were fulfilled; a second stage in which the validation and application of the theoretical concepts and approaches were compiled; the third and last stage encompassed the field work and actual experimental analysis, of everything that was developed in the two previous stages. The impact on the energy efficiency, as well as the economic and environmental impacts, were assessed in every stage and compared among them. A synthetic diagram of all the different scopes and parts of the research can be seen in Figure 3.1. These stages can be found independently along this thesis in the different sections comprised between Chapter 5 and Chapter 8.

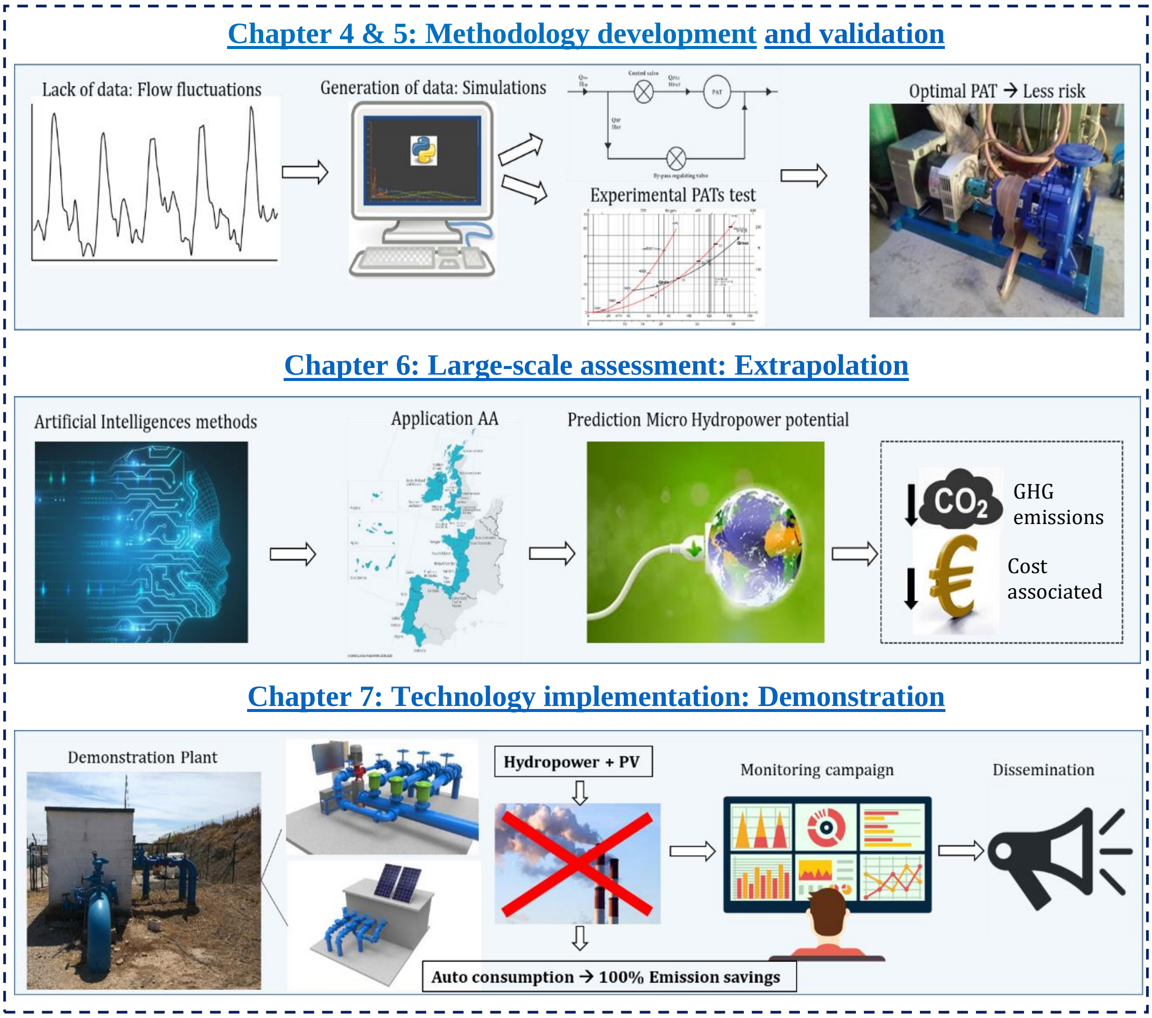

Figure 3-1. *Research model*

3.1.1. Theoretical approach

Regarding the theoretical part of the research, it aimed to address a crucial issue found in irrigation networks generally for MHP technology, and for PATs particularly: the lack of flow data. This information was the required baseline from which the design and selection of a turbine for energy recovery. Thus, the desk work part was focused on the accurate prediction of flow variations with a limited amount of input parameters. This could be of great help for irrigation district's managers, since they could feasibly obtain this distribution to make viability studies for implementing hydropower in the networks. However the use of the flow variation predictions in the networks could have many uses aside from hydropower design. In addition, the theoretical behaviour of PATs depending on the flow variations and design point was added in the model, characterising how its installation would affect to the network operability.

3.1.2. Feasibility evaluation

A model based on theoretical calculations should be tested and validated comparing the predicted data to actual observations. If the theoretical values match with the real ones, the validity of the model could be confirmed. Otherwise, the model should be adjusted for the data calculated to be more feasible. Different statistical indices were used to measure the difference between both values and ascertain the accuracy of the model. Once tested and calibrated, the method could be used in similar networks.

3.1.3. Extrapolation

One of the biggest uncertainties found in the hydropower in water networks is the quantification of its potential in large geographical scale. Previous studies have focused only on case studies of single networks, which does not inform us about the wider sector level potential. Conducting a large scale assessment would facilitate the estimation of the benefits to which this solution would lead and have an idea of the investment required to insert it in the current settings in the sector. Through the application of the accurate theoretical model in many networks with similar properties, a wide data set could be obtained. Then, looking for parallels between the hydropower potential and regional irrigation variables, a more sophisticated technique could be employed to quantify the potential and its impact.

3.1.4. Real-scale and experimental application

The fieldwork and experimental analysis were related with the construction of an experimental demonstration plant in an actual irrigation network. Its main target was the complete replacement of a diesel-source energy generation, being capable of completely feeding the energy requirements of a local farm with hydropower. Therefore, it would ensure a reduction of 100% of the emissions associated to the previous energy system and a significant economic saving due to the avoidance of diesel purchase. Different settings, discussed in previous investigations, were tested on it evaluating their pros and cons, which will be useful for future installations. It will have also an added value: reducing the food production costs and carbon print.

3.2. Research scope

This thesis is also part of the multidisciplinary REDAWN project (Reducing Energy Dependency in Atlantic Area Water Networks). REDAWN aims to assess and foster the adoption of hydropower technology in existing water networks within the European Atlantic Area (see Figure 4.2) as a potential innovative and feasible measure to recover the existing energy and improve energy efficiency. It is part funded by the European Regional Development Fund (ERDF) through the Interreg Atlantic Area Programme 2014-2020.

Trinity College Dublin (TCD) is leading one of the eight work packages that comprise REDAWN, as well as directly participating in most of the other seven. Gather the existing information, the assessment of the existing potential and the extrapolation to the whole AA are the main targets of TCD as project leader of WP4. In addition, three real scale demonstration plants were constructed in three different water activities (drinking, process industry and irrigation), for which TCD has directly participated in the viability study, pre-design of the installation and tender process.

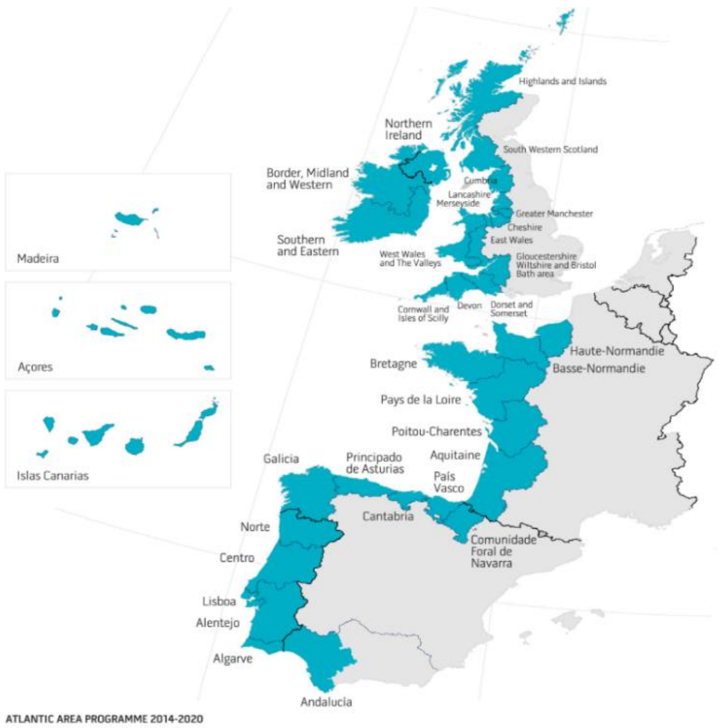

Figure 3-2. *Atlantic Area region*

3.3. Summary

According to the structure and objectives defined in Chapter 1, and the research model presented in this Chapter, the four stages previously exposed will be addressed in the thesis in the following chapters: Theoretical approach (**Chapter 4**), Feasibility evaluation (**Chapter 5**), Extrapolation (**Chapter 6**) and Real-scale and experimental application (**Chapter 7**).

4 FLOWS PREDICTION AND ENERGY RECOVERY METHODOLOGY

4.1. Introduction

The fluctuations in water demand in on-demand irrigation networks were previously defined as particularly important. This kind of infrastructure allows greater flexibility to the farmers since water is available at any time every day and year, and the flow circulating at any point of the network depends on the number of downstream hydrants that are open (Rodríguez Díaz et al. 2007). Therefore, depending on the combination of open and closed hydrants, the flow and head at an issue point varies greatly. When analysing MHP installations, these variations will directly affect the energy recovery as flow vary from zero during winter periods to maximums in July and August, coupled with very large daily and hourly variations. Designing MHP for these conditions requires careful consideration and unique solutions.

To characterise a network and the different monthly flow values, statistical methods are commonly used based on the probability of each hydrant being open or closed. Several methods have been used to calculate the monthly open hydrant probability. Rodríguez Díaz et al. (2007) stated that the gamma function adjusts better to this demand than other distributions, but local farmers' practices and the desired constraints of the network have to be taken into account. However, Clément's methodology (Clement 1966) requires fewer initial data and several previous investigators concluded that the methodology provides good approximate values that can be used to design on-demand irrigation networks (Monserrat et al. 2004; Rodríguez Díaz et al. 2007).

In this chapter, an advanced statistical methodology is developed to predict the flow variations and determine the power available for energy recovery through radial PATs in on-demand irrigation networks. The methodology is applied to the common scenario where no flow data are recorded within the irrigation network and seeks to minimise the PAT investment payback period. The methodology is developed and applied in a real case study in Southern Spain. This methodology uses statistical methods to estimate the variability of flows and heads during the irrigation season. It also provides a useful tool to select the PAT with the lowest payback period for pre-selected locations.

4.2. Materials and Methods

4.2.1. Methodology

The proposed methodology is based on the characterisation of the monthly behaviour of the network through the statistical experiment known as a Bernoulli Experiment. The experiment results define the value domain of the flow, considered a random variable Q, and their occurrence probabilities each month. The objective was to determine the PAT power for each selected Excess Pressure Point (EPP), while minimising the PAT installations payback period (PP). Experimental curves approximating the head recovered and the relative PAT efficiency, both depending on the flow rate together with the flow-head (Q-H) curve of the system, were used to estimate the power ranges and energy recovered. The methodology was defined as a general strategy for reducing the investment risks for PAT installations in irrigation networks. The methodology schematic diagram can be seen in Figure 4-1 and it is divided into five main steps, explained below:

4.2.1.1. Location of excess pressure points and calculation of downstream open/closed hydrant combinations.

The first stage in Figure 4-1 was to simulate the network's hydraulic performance and find the excess pressure points along it, considering a pre-set hypothesis, such as design hypothesis or 100% of hydrants open. Considering all hydrants to be open presents the worst case scenario with maximum head losses and minimum pressures. Any excess pressure available in this condition will therefore be available all year around as a conservative minimum.

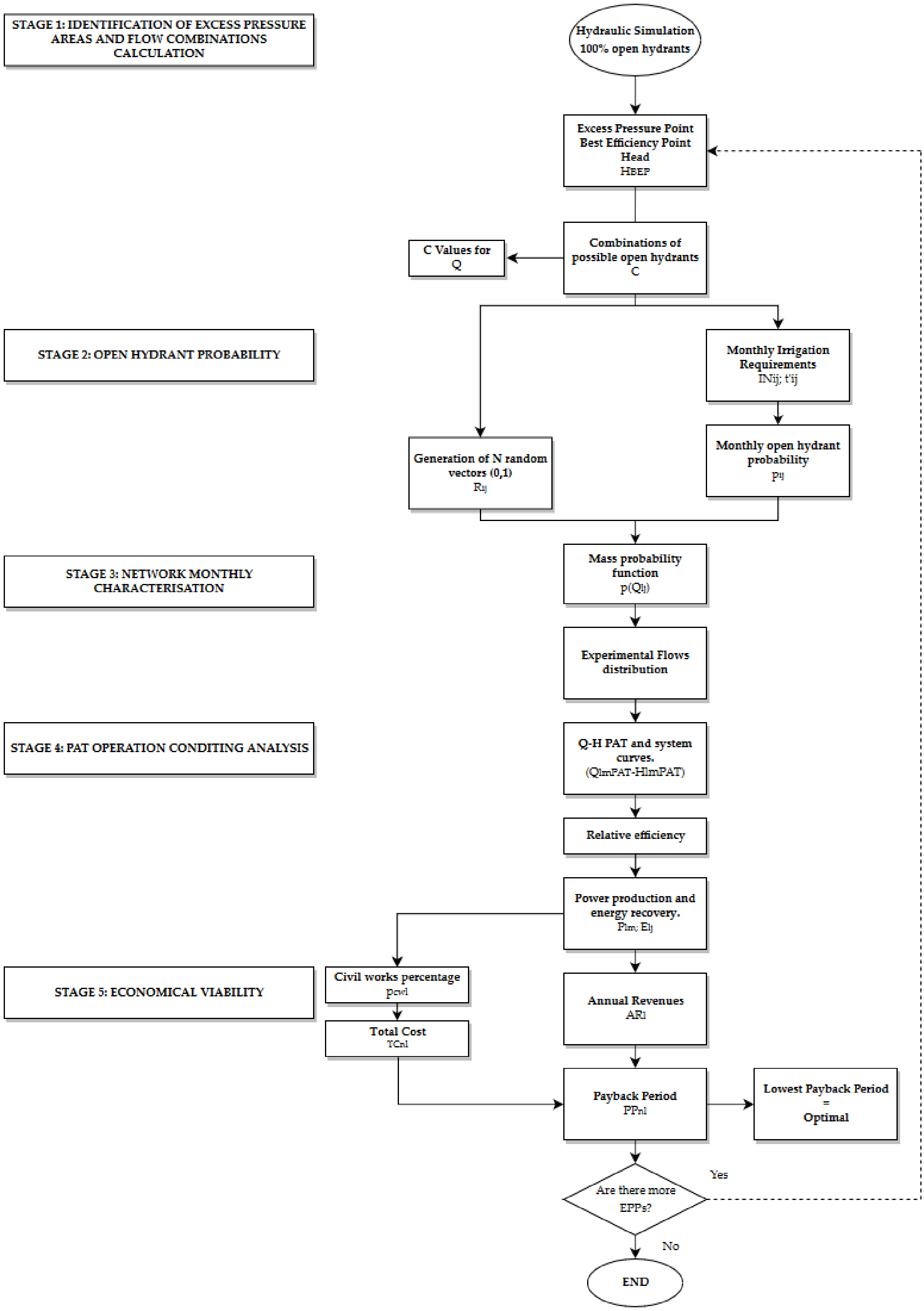

Figure 4-1. *Flowchart of the methodology*

Within this first step, the next boundary condition was applied: BEP head (H_{BEP}) is equal to the head available for each EPP in the first simulation under the hypothesis used, ensuring no lack of pressure in any scenario. H_{BEP} had the same value for every scenario analysed within each EPP. Novara et al. (2019) presented a Q-H space to locate the BEP conditions for a large set with 323 PATs, showing several points where the head could reach up to 3m for certain flows (see Figure 4-2). Considering this space, the minimum head (excess pressure) for a point to be evaluated as an EPP was fixed at 3m above the service pressure.

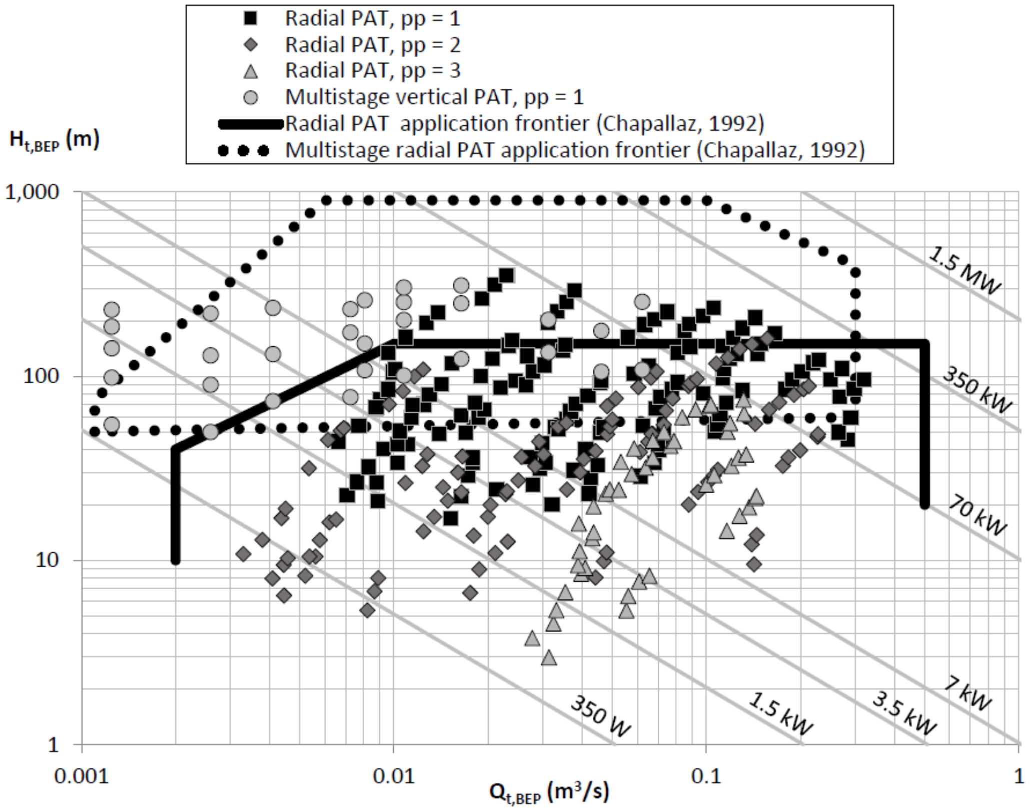

Figure 4-2. *Location of the estimated PAT Best Efficiency Points (BEP) for the 323 selected machines over the H-Q space (Novara et al., 2019).*

The flow fluctuations depended on the crop irrigated by each hydrant and their water requirements along the irrigation season. These fluctuations defined the values of the domain of the random variable Q, and were analysed through a Bernoulli Experiment. Hence, in each EPP, the range of possible values for Q was determined depending on the amount of possible combinations of downstream open/closed hydrants. Supposing a number of hydrants n, the number of possible combinations C, was calculated as defined by Equations (4.1) and (4.2), for a random combination of open hydrants a, with $0 \leq a \leq n$. Each combination represents a different distribution of open/closed hydrant downstream the EPP analysed. In the scheme shown in Figure 4-3, 11 hydrants can be found downstream the EPP. A random combination *a* for this EPP is represented, where four hydrants (H1, H4, H7 and H10) are open. The flow at the EPP will vary depending on the combination of open hydrants, as another combination of four open hydrants different to the one shown in the Figure would return a different flow running through the EPP. Thus, the analysis of these combinations is important, as it will define the range of the flow values.

$$C = \binom{n}{0} + \binom{n}{1} + \binom{n}{2} \dots + \binom{n}{n} \tag{4.1}$$

$$C_a^n = \binom{n}{a} = \frac{n!}{a!\,(n-a)!} \tag{4.2}$$

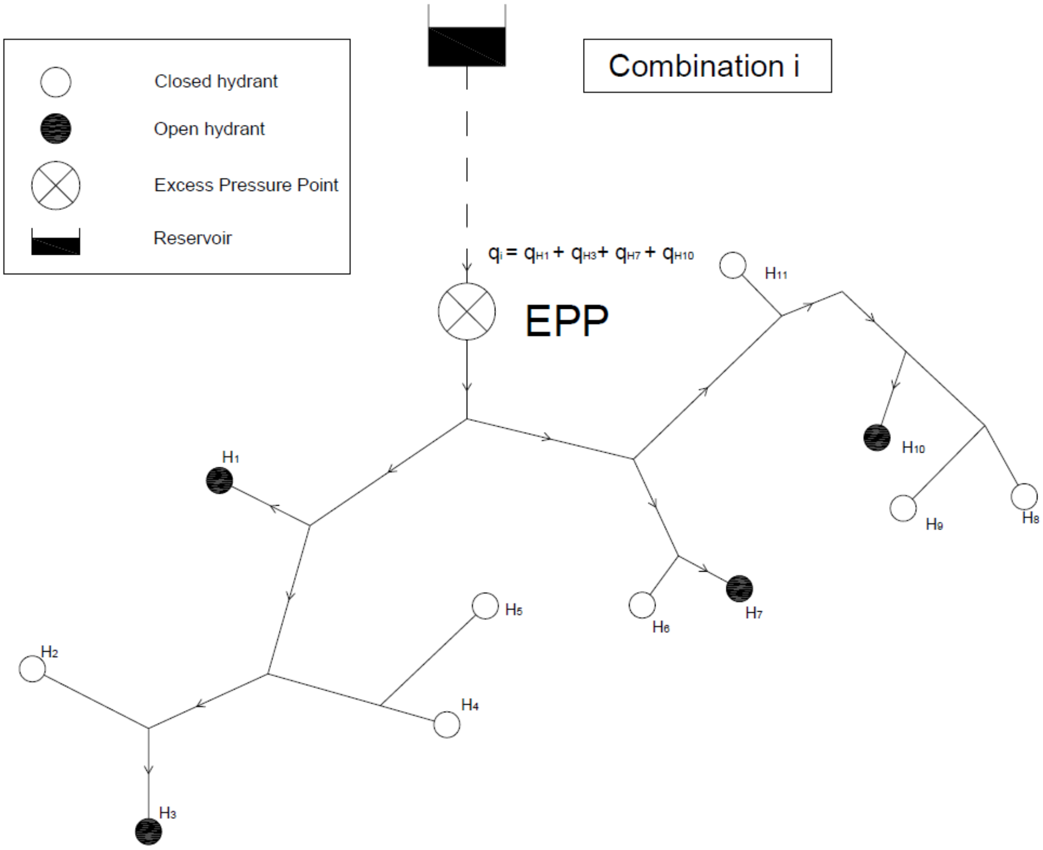

Figure 4-3. *Random combination of downstream open hydrant for a general EPP.*

4.2.1.2. Open hydrant probability calculation

This step aimed to calculate the monthly probability of each hydrant to be open. To obtain these probabilities, the formula proposed by Clément (Clement 1966) was used. The distribution of crops irrigated by each hydrant and their monthly irrigation requirements were needed. Hence, the monthly water requirements matrix, IN_{ij} (l ha^{-1} month^{-1}), was obtained, with *i* referring to the hydrant and *j* to the month.

Clément defined that one hydrant has two possible working states, open, with a probability of *p*, and closed with a probability of *1-p* (Clement 1966; Lamaddalena and Sagardoy 2000). Thus, the monthly probability of an open hydrant (p_{ij}), defined in Equation (4.3), was estimated as the relationship between monthly irrigation hours required by the crops, associated to each hydrant, t'_{ij} (hours month^{-1}), and the monthly water availability, T'_{ij} (hours month^{-1}) for each hydrant *i* in each month *j*. These were calculated following Equations (4.4) and (4.5) respectively. Finally, $hours_i$ refers to the daily water availability (hours) per hydrant and $days_j$ (days month^{-1}) to the number of days in the month *j*. q_{max} is the design flow allowed per unit of irrigated area.

$$p_{ij}= \frac{t'_{ij}}{T'_{ij}} \tag{4.3}$$

$$t'_{ij} = \frac{1}{3600}\frac{IN_{ij}}{q_{max}} \tag{4.4}$$

$$T'_{ij} = hours_i \; days_j \tag{4.5}$$

4.2.1.3. Irrigation requirements calculation using CROPWAT

The CROPWAT software is a tool developed by the Land and Water Development Division of the FAO. The calculations conducted by the software are based on the methods proposed by Allen (1998) and by Doorenbos et al. (1980), which dealt with the computing crop water requirements and crop yield response to water respectively. The FAO recommends that the software should be used just when no local information about the crop irrigation volume to be applied is known.

This was one of the first challenges faced in this thesis, since the complexity to gather information on the irrigation sector is quite high, considering the large areas involved, large varieties of crops and numbers of individual farms. This lack of actual information regarding actual volumes used for irrigation was therefore fulfilled using CROPWAT, which returned the theoretical crop irrigation volumes to be applied. The final output searched for this thesis was the crops irrigation requirements, calculated based on the local characteristics of the area analysed. These requirements could be obtained either every day, 10 days or monthly, and they were needed to calculate the probability of each hydrant to be open or closed. As it was stated before, the monthly values were calculated, as values every ten days would increase exponentially the computational time required to obtain the flows variability.

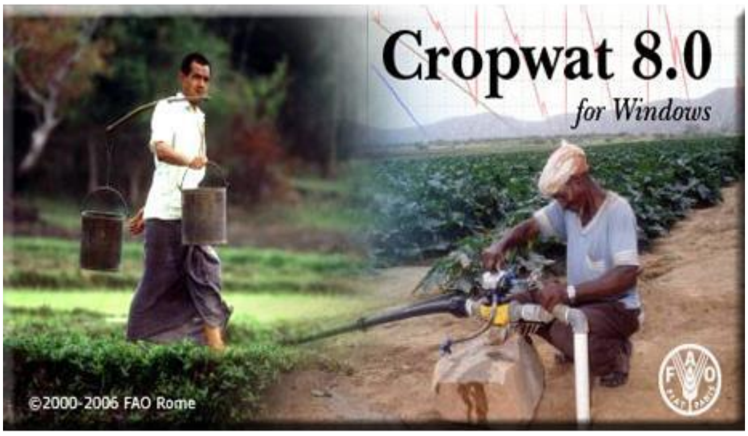

Figure 4-4.*CROPWAT logo*

To make all the calculations the software asked for four inputs; i) evapotranspiration; ii) rainfall; iii) crop properties; iv) soil properties.

The evapotranspiration (ET_o) is inputted in daily values, whilst monthly cumulative values are inputted for the rainfall. These data can be gathered from climatic stations close to the study area. Inputting them into CROPWAT, it directly estimates the effective rainfall. Then, the crop properties have to be defined. Among others, the planting date, the crop coefficient (K_c) along the different season stages (initial, mid and end of the season stage), the duration of each stage in days or the yield response factor, all have to be defined. The crop coefficient is defined in order to take into account the effects of both crop and soil evapotranspiration. The values for each parameter can be found in the "*Crop Evapotranspiration - Guidelines for computing crop water requirements*" (Allen, 1998). The crop evapotranspiration is estimated following Equation 4.6:

$$ET_c = K_c ET_o \tag{4.6}$$

The results obtained for the crop water requirements can be seen graphically in Figure 4-4. The crop water requirements (*IN*) obtained at this stage are used to calculate the crop irrigation time (*t'*) previously defined as per Equation 4.5, needed to calculate the open probability of a hydrant.

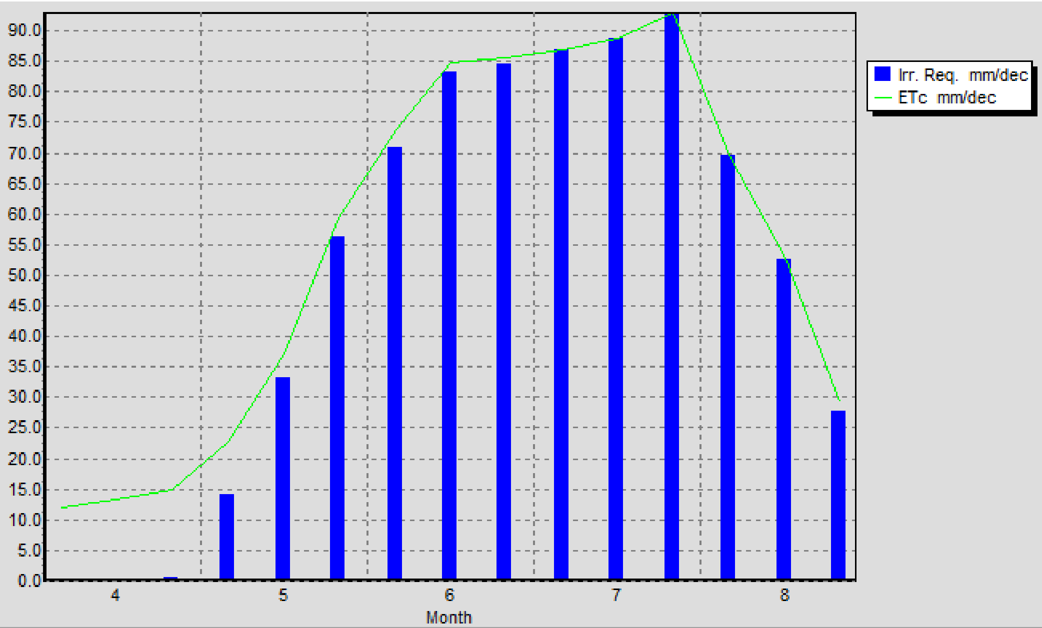

Figure 4-5. *Graphic results obtained in CROPWAT for crop evapotranspiration and crop irrigation requirement.*

4.2.1.4. Monthly characterisation of the network: Mass probability function, $p_X(x)$ calculation.

The Bernoulli Experiment involved repeated independent trials of an experiment, called Bernoulli Trials (BTs), with two possible outcomes, arbitrarily called success (S) and failure (F) (Olkin, 1980). Knowing that the trials are independent and assigning the value 1 to S and 0 to F, the combinations of open and closed hydrants downstream of the EPPs were obtained, depending on the results of the trials. Therefore, every BT had two possible outcomes, $X = 1$ is understood as success, and the issue hydrant is open. On the other hand, if the result was $X = 0$, then the result is failure and the issue hydrant is closed. Depending on the number of possible downstream open hydrant combinations (*C*), a number of BTs, N, is defined, since the greater the number of hydrants the greater the number of combinations, and so the greater the domain of Q. *N* will be at least double the number of combinations, in order to obtain every possible combination. Thus, every BT consisted of the generation of *N* random vectors, R_i, with values between [0, 1], and its comparison with monthly probability of each hydrant to be open. The results obtained in each BT followed Equations (4.7) and (4.8):

$$If\ R_i > \ p_{ij} \rightarrow X = 0 \tag{4.7}$$

$$If\ R_i \leq \ p_{ij} \rightarrow X = 1 \tag{4.8}$$

The aim of the BTs was to generate matrices with dimensions [N x j], which contained all the possible monthly values of the domain of the random variable Q, depending on the different combinations of open and closed hydrants. With these matrices, the behaviour of the network downstream of the EPPs could be characterized on a monthly basis.

The Bernoulli Experiment was run integrating the EPANET engine into Python (v2.7.15) through its Dynamic Link Library (DLL). Bernoulli distributions were obtained after each trial. These distributions are directly related with the Binomial distribution. The Binomial distribution is defined by the number of independent trials carried out, *N*, and the probability of success, *p*. When the number of trials is 1, then the Binomial distribution is called a Bernoulli distribution. Therefore, the results obtained for every EPP composed the domain of Q. Analysing these results, the monthly flow values and their occurrence probability could be calculated. Hence, for each EPP, 12 (monthly) Binomial Distributions were obtained.

The probability mass function of a discrete random variable X conveys the same information as a table of probabilities of simple events for the possible values of X (Olkin, 1980). Thus, after calculating every possible flow value Q_l, the next step was to calculate how often these values occur monthly. The mass probability function for the whole domain was obtained dividing the times, n_{lj}, that each value Q_l was repeated in each month *j*, by the number of total BTs (N). The occurrence probability of each flow value was obtained following Equation (4.9).

$$p(Q_{lj}) = \frac{n_{lj}}{N} \tag{4.9}$$

A comparison between the monthly experimental volume and the monthly theoretical volume required was made in each EPP. Its aim was to check how good the experiment fitted with the theoretical values. To calculate the monthly experimental volumes per unit of irrigated surface, the monthly flow distributions and their probabilities were required. Applying Equation (4.10), the monthly experimental volumes were calculated as:

$$EV_j = 3600\, T'_{ij} \frac{q_{max}}{q_M} \sum_{l=1}^{C} Q_l\, p(Q_{lj}) \quad (4.10)$$

Where EV_j is the monthly experimental volume; q_{max} is the design flow allowed per unit of irrigated area; q_M is the maximum flow circulating through the EPP.

4.2.1.5. PAT operating conditions analysis

The different demand patterns and available existing head makes necessary the installation of a regulation system to control the working conditions of a PAT. This regulation has been proposed to be done using either hydraulic or electric devices.

When the conditions are hydraulically controlled by means of control valves, the scheme is denominated hydraulic regulation (HR). This solution generally comprises of two valves, one in series and one in parallel to the PAT. The valve in series duty is to dissipate the head exceedance that cannot be used by the PAT. While the valve in parallel fixes the backpressure required of the flow diverted, moving the flow and head on to the PAT curve. When the head at the network is greater than the head drop caused by the PAT, the valve in series dissipates the exceedance. For larger flows, PATs tend to have greater head drops, reducing the backpressure below than the value required. At this point is where the parallel valve starts operating, offering less resistance for the water to stream, hence reducing the flow running through the PAT. These operating rules are latterly shown in Figure 4-5, where the range of points for which the in series and parallel valves are marked by the intersection point between the network curve and the PAT characteristic curve.

Another other way proposed to regulate the turbine working conditions is through electric devices, which are able to adjust the rotational speed increasing or decreasing the pair moment of the PAT, and thus the resistance of the water to run through the turbine. This duty is normally carried out by a variable speed drive (VSD), which moves the characteristic curve of the PAT adjusting its operation point to the existing conditions at the network.

Lastly, the combination of both regulation schemes can be used, installing the hydraulic valves in the bypass scheme and the VSD to adjust the existing conditions after the hydraulic regulation to the PAT characteristic curve.

The strategy employed followed that known as Variable Operating Strategy (Carravetta et al. 2012), which aims to design PATs installation considering the variation of the working conditions. This strategy takes into account the different flow and head values, and how the PAT performance would vary under these conditions. Carravetta et al. (2012) suggested the following criteria for PAT VOS design:

1. Flow rate and head variations should be available in order to determine the available head depending on the required backpressure.
2. PAT type should be considered.
3. A broad number of PAT characteristic and efficiency curves should be considered and theoretically tested.
4. For each curve, the overall plant efficiency is calculated.
5. The PAT maximising the energy production is selected as the optimal design solution.
6. The near-optimal machine is selected from the market.

Most of the steps recommended by Carravetta et al. (2012) were followed in this methodology, but with small changes. Firstly, as it was previously stated, it is significantly tedious to find actual flow or head records, due to the lack of recording devices in irrigation networks. Hence, a need existed to predict the flow fluctuations, which was explained in the subsections 1-4 of the methodology section of the present chapter. In this way, the first requirement to apply the VOS was fulfilled. The PAT types were not considered, as the methodology supposed a theoretical approach to study the potential and viability of MHP within irrigation networks. Regarding the third consideration proposed, an extensive number of PATs were tested, as every BEP flow within the flow domain was used to obtain different PAT characteristic and efficiency curves. For the efficiency of the PATs, the relative global performance depending on the flow rate was estimated and considered for each PAT. A small change was introduced in this methodology with regard to the fifth point. The minimisation of the payback period was defined as objective function, as the viability of each plant depends on the return of the investment rather than in the energy produced. Finally, the sixth point was not taken into account in the current method, as it proposes a theoretical approach rather than the actual design, which is addressed in Chapter 7. Therefore, this method could be defined as a simplified VOS for PAT installation feasibility assessment and design for on-demand irrigation networks.

In this methodology, every possible flow circulating through the EPP pipe was considered as a possible BEP flow of a theoretical PAT to be selected. Hence, *l* different scenarios were defined, each of them corresponding to one PAT, whose BEP was (Q_{lBEP}, H_{BEP}). To regulate the PAT inlet conditions and keep the network service conditions downstream, the by-pass scheme proposed by previous researchers (Carravetta et al. 2014a; Lydon et al. 2017a), has been considered, in which there are two control valves, one before the PAT and the other in parallel. This HR scheme, was used in this methodology, since previous investigations concluded that HR is generally more efficient than electric regulation, showing larger efficiencies when the working conditions vary from the design values. In addition, they were also shown to be less expensive (Carravetta et al. 2014a). This can be observed in Figure 4-5.

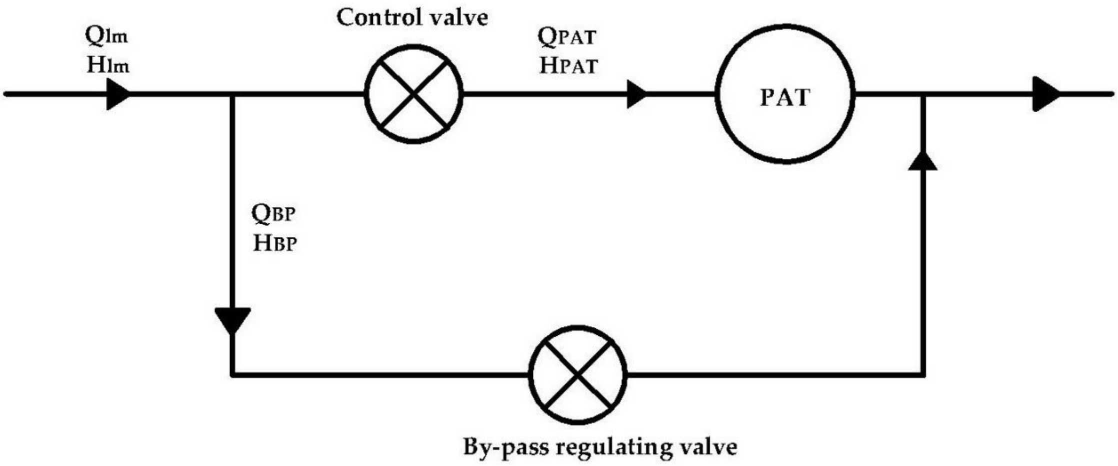

Figure 4-6. *Typical HR PAT installation scheme (Carraveta et al., 2012)*

The methodology followed to estimate the flows running through the turbine, simulated the interaction between the Q-H system and PAT curves. The two operating rules fixed were: i) the flow demanded downstream of the EPP would fully circulate through the turbine if its value is lower than or equal to the maximum flow to be turbined Q_{lMAX} in each scenario *l* (This value was calculated obtaining the intersection between both, PAT and system Q-H curves); ii) if the flow demanded downstream is greater than the maximum fixed for each scenario Q_{lMAX}, this flow would be diverted to the by-pass. To obtain the amount of flow diverted in each scenario l for each flow demanded downstream m, Q_{lmBP}, the interaction between both system and PAT curves is required again.

Operating Rules

i) $If\ Q_{lm} \leq Q_{lMAX}$ $\begin{cases} Q_{PAT} = Q_{lm} \\ Q_{lmBP} = 0 \end{cases}$

ii) $If\ Q_{lm} > Q_{lMAX}$ $\begin{cases} Q_{PAT} = Q_{lmPAT} \\ Q_{lmBP} = Q_{\text{lm}} - Q_{lmPAT} \end{cases}$

The methodology assumes that the selection of a pump to operate in reverse as a turbine with the specified BEP can be carried out independently, using the approach described in Lydon et al. (2017a). This approach used different analytical methods that converted different ratios related to the BEP of a pump to that of a PAT. In this research, the method adopted the approach proposed by Barbarelli et al. (2017) to estimate the PAT characteristic curves (head & flow). Barbarelli, proposed an alternative curve to the curve suggested by Derakhshan and Nourbakhsh (2008) to obtain the relative head for any given machine based on 12 pumps tested as turbines. This curve followed Equation (4.11). The method presented a coefficient of determination of 0.923, thus providing a significant accuracy when estimating PATs' behaviour. Although other methods returned a slightly better accuracy, the difference was insignificant, while the method used was based on a greater database than previous method and was simpler to apply. Thus, all the relative heads were obtained for every flow demanded downstream Q_{lm} in the scenario *l*. The value of the head recovered by the PAT H_{lm} was calculated multiplying the relative heads by the BEP head, H_{BEP}. With these heads quantified for every PAT associated to every scenario *l*, all the Q-H curves for the specific system were obtained. These equations had the form of Equation (4.12), where the coefficients changed for each hypothetical PAT tested.

$$\frac{H_{lm}}{H_{BEP}} = 0.922\left(\frac{Q_{lm}}{Q_{lBEP}}\right)^2 - 0.406\left(\frac{Q_{lm}}{Q_{lBEP}}\right) + 0.483 \quad (4.11)$$

$$H_{lmPAT} = aQ_{lmPAT}^2 + bQ_{lmPAT} + c \quad (4.12)$$

Where H_{lmPAT} is the head recovered for a certain flow Q_{lmPAT} running through the PAT. In Figure 4-6, this interaction and intersection between a potential PAT and the system curve for a random site is displayed. To calculate the amount of flow turbined and the amount diverted through the by-pass, every possible flow value greater than Q_{lMAX}, was introduced in the system curve, obtaining the head available ($H_{lm-System}$) in the system for such a flow (Q_{lm}). Using this head ($H_{lm-System}$) in the PAT curve as the head recovered (H_{lmPAT}), the flow circulating through the PAT was fixed. Applying this sequence to every possible flow greater than Q_{lMAX}, all the pairs (Q_{lmPAT}, H_{lmPAT}), for which the device could work, were calculated. Consequently, in scenario l, the portion of flow diverted through the by-pass for values greater than Q_{lMAX} was the difference between the flow demanded downstream and the flow turbined ($Q_{lm} - Q_{lmPAT}$).

Each of these pairs (Q_{lmPAT}, H_{lmPAT}) had an associated relative efficiency, under which the PAT operates. Novara and McNabola (2018) proposed a model, through the extrapolation of 116 measured PAT characteristic curves, estimating the behaviour of their relative efficiency depending on the flow rate. Thus, the mechanical relative efficiency was obtained for each flow, Q_{lmPAT}, in scenario l, following Equation (4.13). As a conservative estimate the maximum efficiency was fixed at 55% (0.65 PATs + generator efficiency and 0.85 to take into account the hydraulic regulation losses) (Carravetta et al. 2012). For very low flow rates, this relative efficiency has negative values, for which the device should be switched off or the flow would be diverted. The power production for each scenario l, whose BEP is (Q_{lBEP} , H_{lBEP}), for each pair (Q_{lm}, H_{lm}), was obtained as per Equation (4.14).

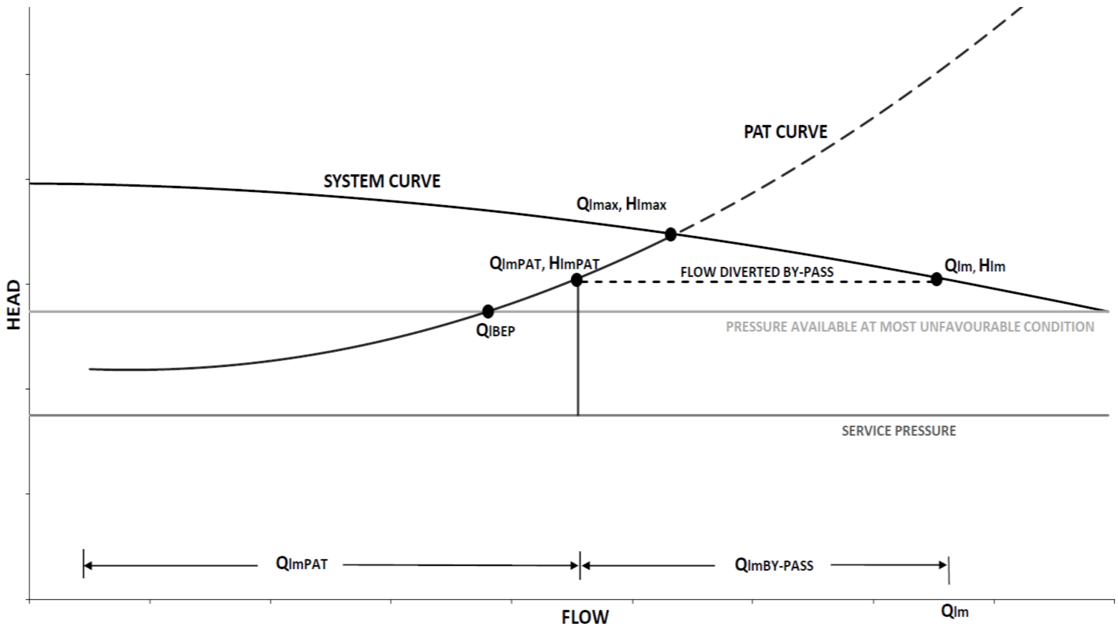

Figure 4-7. *Representation of a potential PAT flow-head curve for a hypothetical site, and working pairs (Q_{lmPAT}, H_{lmPAT}) for a random flow Q_{lm} greater than the maximum Q_{lMAX} in the Q-H space.*

$$\eta_{lm} = 0.5197 \left(\frac{Q_{lmPAT}}{Q_{lBEP}}\right)^3 - 2.3328 \left(\frac{Q_{lmPAT}}{Q_{lBEP}}\right)^2 + 3.0931 \left(\frac{Q_{lmPAT}}{Q_{lBEP}}\right) - 0.2757 \quad (4.13)$$

$$P_{lm} = 0.55\, Q_{lmPAT}\, H_{lmPAT}\, \gamma\, \eta_{lm} \quad (4.14)$$

Where Q_{lBEP} is the value of the BEP flow for each scenario *l*; γ is the specific weight of the water; η_{lm} is the relative efficiency value for each pair for scenario *l*. Lastly, to estimate the monthly energy recovered, the powers produced by each PAT for each pair (Q_{lmPAT}, H_{lmPAT}) in scenario *l* were used, together with the monthly mass probability function and the monthly available time. The monthly available time matrix was reduced to a single vector, since it was an on-demand irrigation network, where every hydrant had 24 hours of availability every day of the year. Its calculation followed Equation (4.15).

$$E_{lj} = P_{lm}\, p\left(q_{lj}\right) T'_j \quad (4.15)$$

4.2.1.6. Economic viability

The last stage of the methodology was to assess the economic viability of each scenario studied. Payback Period (PP) was used here to determine the period needed to recover the investment made, neglecting the time value of money.

To quantify the total installation cost, three different main components have been considered: electromechanical (PAT + generator), civil works and additional works. Regarding the electromechanical part, different investigations have given different approaches. Ramos et al. (2009) estimated the cost of a PAT to vary between 200-400 €/kW for nominal power lower than 40 kW. Carravetta et al. (2013a) proposed the sum of nominal power of the turbine, 230 €/kW, and the maximum PAT power accounting for the cost of the generator, 115 €/kW. De Marchis et al. (2014) proposed a cost per power unit of 2,000 €/kW for PAT plus generator. In this research, a cost model, which estimates the unitary price for PAT and generator, has been used. This model estimates different kinds of radial PATs, including generator with 1, 2 or 3 pairs of magnetic poles (pp) (Novara et al. 2019). The cost per kW of the centrifugal PATs coupled with induction generators with the number of pp mentioned is related to the parameter $Q_{lBEP}\sqrt{H_{BEP}}$. Thus, the electromechanical cost has been calculated for every possible BEP flow value and the BEP head was fixed, using Equations (4.16), (4.17) and (4.18).

$$C_{PP1l} = 11{,}589.32\ Q_{lBEP}\sqrt{H_{BEP}} + 1{,}380.79 \tag{4.16}$$

$$C_{PP2l} = 12{,}864.77\ Q_{lBEP}\sqrt{H_{BEP}} + 949.43 \tag{4.17}$$

$$C_{PP3l} = 15{,}484.97\ Q_{lBEP}\sqrt{H_{BEP}} + 1{,}172.72 \tag{4.18}$$

In addition to the PAT costs, other works have to be added, such as civil work and the cost of the by-pass. Regarding the civil works, a new approach has been developed within this research. The percentage of the civil works costs depending on the power installed was calculated using Equation (4.19), proposed in this research. For additional works, such as electric connection or maintenance, 20% of the total costs has been considered. Following Equation (4.20), the total costs for the installations were obtained as:

$$p_{cwl} = 1 \cdot 10^{-7} P_{lBEP}^{4} - 2 \cdot 10^{-5}\ P_{lBEP}^{3} + 0.0011\ P_{lBEP}^{2} - 0.0349\ P_{lBEP} + 0.6714 \tag{4.19}$$

$$TC_{nl} = \frac{CC_{PPnl}}{(1 - p_{cwl})\ 0.8} \tag{4.20}$$

Where p_{cwl} is the percentage of the civil works over the total installation cost in scenario *l*, and C_{PPnl} is the total installation cost for each flow value and number of polar pairs, *n*, of the electromechanical devices. To complete the economic analysis, the calculation of the annual revenues (AR) and the PP was carried out. For the first term, the total energy produced in each scenario has been multiplied by the income rate, in case of selling to the grid, or the energy tariff in case of auto consumption. This rate will depend on the country where the installation is made. Thus, applying Equations (4.21) and (4.22) the AR and PP for each scenario was calculated:

$$AR_l = \sum_{j=1}^{12} E_{lj} r_j \tag{4.21}$$

$$PP_{nl} = \frac{C_{PPnl}}{AR_l} \tag{4.22}$$

Where E_{lj} is the monthly energy recovered in each scenario *l*; the vector r_j represents the money received or saved per kilowatt every month. Finally, analysing all the PPs associated to scenario *l* and every potential PAT, *n*, the selected scenario would be the one whose PP is the lowest, considering the respective BEP power to be installed. It has to be highlighted, that for MHP technology, the PP has to be lower than 10 years (Corcoran et al. 2013) to be considered economically viable in the water sector. Thus, of all the points studied, those with $PP \geq 10\ years$, were discarded.

The description of the civil works considered in this research is explained below. Previous investigations stated that the civil work costs could be taken into account as a fixed percentage of the total installation, independently on the PAT costs and power. This consideration does not match with reality since the civil works to be made will depend on the power to be installed, and its cost then. Therefore, for general cases, the percentage represented by the civil works would depend on the power of the PAT, or rather, the PAT cost. The method proposed in this thesis, is based in the estimation of the parties that would be involved in a general PAT installation in irrigation networks. Concrete foundation for the PAT, earthworks, materials and construction of the by-pass, backfilling and protection house have been considered as general parties for a general PAT installation in these infrastructures. In some cases, the parties involved would be less and in some cases greater. Nonetheless, this approach provides a better estimation of the civil works, since they will be almost the same for any specific point, independently of the power to be installed. Thus, it can be said that the lower the power is, the higher percentage will be represented by the civil works in the total costs. A brief bill of quantities (BOQ), whose unitary prices has been fixed from the Spanish Price Generator for Construction Database [41], is explained in the Table 4-1. From this BOQ, Figure 4-8, which shows the percentage represented by the civil works over the total installation costs, has been developed.

Table 4-1. *Parties accounted in the civil work costs.*

	CIVIL WORKS				
CW.1	Manual trench excavation (20 x 2 x 1.5 m)	m^3	76	€49.45	€3,758.20
CW.2	By-pass: Supply + fixing 300mm ductile iron pipes	Lm	18	€96.35	€1,734.30
CW.3	Reinforced concrete slab 10cm	m^2	8	€16.23	€129.84
CW.4	Protection House: Concrete blocks (40x20x10 cm) supply and fixing (4 x 2 x 2.5 m)	m^2	30	€41.78	€1,253.40
CW.5	Manual back-filling: Same material excavation	m^3	76	€3.54	€269.04
Total					**€7,144.78**

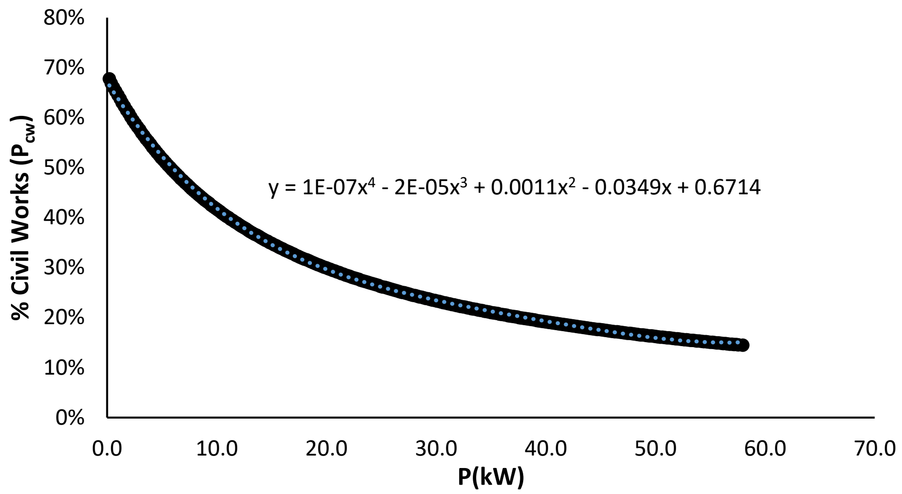

Figure 4-8. *Costs percentage represented by the civil works depending on the PAT power.*

4.3. Study Area

Sector VII of the right bank of the Bembezar River (BMD) is a pressurized water distribution network located in Seville (Spain). The network is composed of pipes with diameters between 150 and 800 mm. It contains 162 hydrants which irrigate a total surface of 920 hectares. The main crops cultivated in the district are: Citrus (56%), maize (32%), cotton (9%) and sunflower (3%). The hydrants are distributed in levels which vary between 47 m and 97 m.

A pumping station is located at 86 m.O.D. and is composed of two kinds of pumps. The first type has a power of 90 kW, and there are three of these units. The second type has a power of 270 kW, and there are two of these units. The network was designed to supply 1.2 l/s/ha on demand, so water is continuously available to farmers (24 hours per day). The network was designed for 100% of open hydrants simultaneity. The methodology developed here has been applied for the 2017 irrigation season, for which the agronomic parameters (rainfall and evapotranspiration) have been considered. The total values of these parameters for the 2017 irrigation season amounted 440 mm and 1,210 mm respectively.

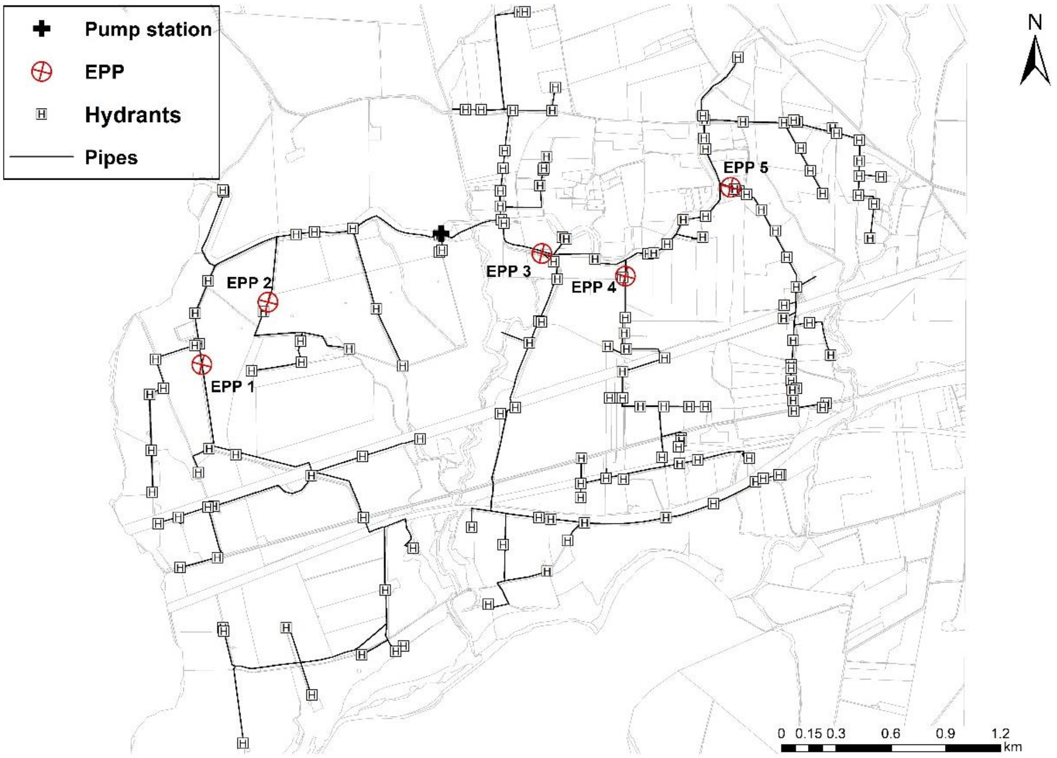

Figure 4-9. *EPPs in the sector VII of the right bank of the Bembezar River Irrigation District.*

4.4. Results

4.4.1. Location of excess pressure areas and calculation of downstream open/closed hydrant combinations.

In this first stage, hydraulic simulation following the design hypothesis, 100% of the hydrants of the network set as open, was conducted, using EPANET (Rossman 2000) As a result, five points have been identified as potential EPPs, with an available excess pressure of 19.1 m, 13.9 m, 19.8 m, 18 m and 14.3 m respectively. In this first assessment, the BEP head for the turbine was fixed, since the first simulation has been carried out under the most unfavourable conditions. In this way, it was ensured that the service pressure reaching the hydrants located downstream was always greater than or equal to the minimal pressure required, 35 m in this case. The location of these points can be seen in Figure 4-7, noting that each EPP was located on a separate branch of the network.

The number of hydrants located downstream of each EPP was then counted, to obtain the number of possible open hydrant combinations, following Equations (4.1) and (4.2).

4.4.2. Open hydrant probability calculation

As there is no record available of the actual open hydrant time, it has to be estimated by means of the formula proposed by Clément (Clement 1966). Regarding the crop distribution, the crops irrigated by each hydrant were also not available, and just the percentage of total land for each crop was known. Therefore, this general distribution has been applied to each hydrant. These two first steps of the second stage could be replaced by actual information in case that the irrigation network studied had this data available.

Thus, firstly, the monthly crop water requirements were calculated. The required irrigation time per hydrant and month was then calculated using Equation (4.4). Specifically, this network is an on-demand irrigation network, so the water availability is 24 hours every day. Then, the monthly probability of open hydrant was calculated for each hydrant using Equation (4.3). Since the crop distribution per hydrant was not available, the general percentage of crops mentioned in the description of the case study has been applied to each hydrant, assuming all of them had the same open hydrant probability, as shown in Table 4.1. The characteristics of each EPP before running the experiment and the input information are shown in Table 4.2.

Table 4-2. *Monthly open hydrant probability by crops depending on the surface occupied, and total monthly open hydrant applied to every hydrant during the irrigation season.*

Crop	**Surface Percentage**	**Monthly Open Hydrant Probability (%)**							
		Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Citrus	56	0.3	4.1	14.7	25.5	28.1	24.4	13.0	1.0
Maize	32	0.0	0.0	7.6	23.8	26.7	14.6	0.0	0.0
Cotton	9	0.0	0.0	1.8	6.0	7.1	4.2	0.0	0.0
Sunflower	3	0.0	0.0	1.1	2.5	2.4	0.3	0.0	0.0
Total (%)	**100**	**0.3**	**4.1**	**25.2**	**57.8**	**64.3**	**43.5**	**13.0**	**1.0**

Table 4-3. *Summary of the EPPs found, downstream hydrants, number of possible flow values, flow range and monthly and yearly number of Bernoulli Trials run conducted.*

EPP	**Downstream hydrants**	**Flow values**	**Q (l/s)**	**Bernoulli Trials**	**Total simulations**
1	23	8,388,608	0-297	17,000,000	204,000,000
2	5	32	0-82	15,000	180,000
3	21	2,097,152	0-179	5,000,000	60,000,000
4	26	67,108,864	0-101	140,000,000	1,680,000,000
5	21	2,097,152	0-75	5,000,000	60,000,000

4.4.3. Monthly characterisation of the network: Mass probability function, px(x) calculation.

Once the monthly open hydrant matrices were defined for every hydrant of the network, several BTs were run, in order to characterise the behaviour of the network across the year. Thus, analysing the results obtained for each EPP it can be seen that the flow values varied from 0-297 l s^{-1}, 0-82 l s^{-1}, 0-179 l s^{-1}, 0-101 l s^{-1} and 0-75 l s^{-1} respectively. From these results, a distribution of the flows along the irrigation season was obtained, and the monthly behaviour of the network could be characterised by analysing the 12 monthly binomial distributions. The mass probability functions were calculated using Equation (4.9).

In Figures 4-9 - 4-11, the mass probability functions corresponding to the months of irrigation season for EPP3 can be seen. The mass probability function illustrates the monthly occurrence probability of every flow of the domain of Q. Higher probabilities can be seen for lower flows in months where the irrigation requirements are lower, and higher probabilities for greater flows in months with more irrigation requirements.

The monthly predicted volumes were calculated using Equation (4.9). The variations between the theoretical and predicted values for the EPPs can be seen in Figures 4-10 - 4-12. The annual variations found between the theoretical and predicted volumes in the five EPPs were -0.0873%, 0.3867%, 0.0816%, -0.08024% and 1.2287% respectively.

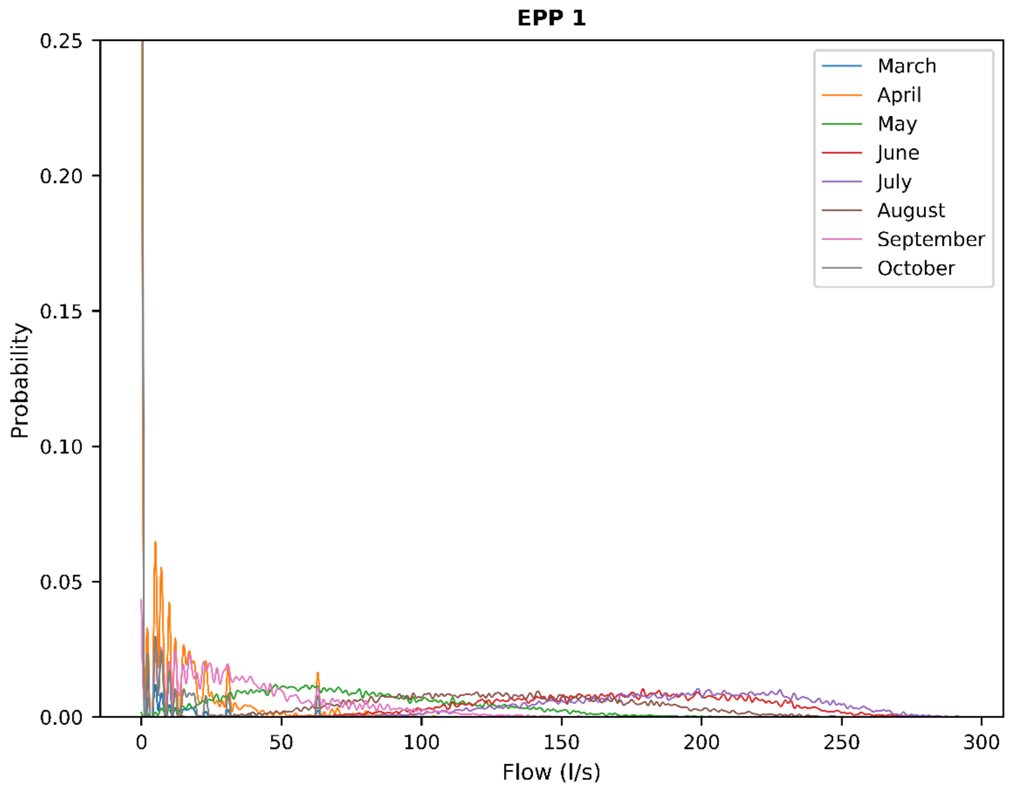

Figure 4-10. *Mass probability functions for the possible flow values during the irrigation season for EPP 1.*

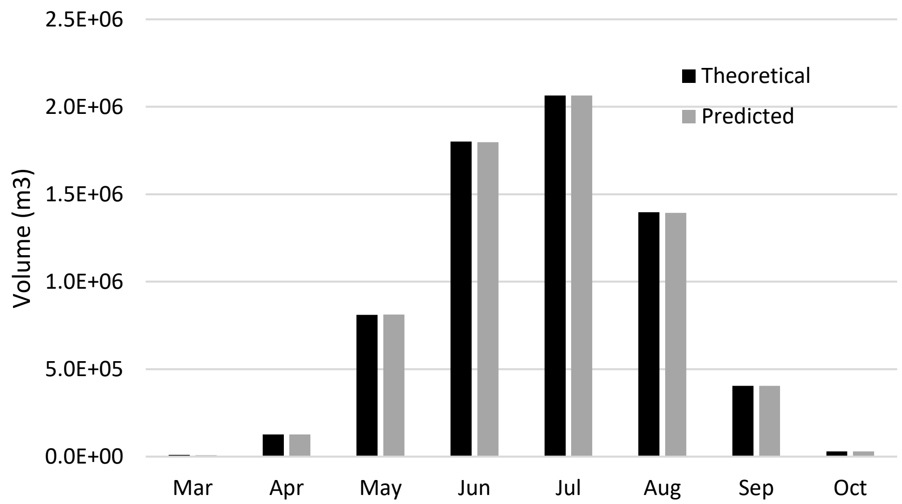

Figure 4-11. *Theoretical irrigation volume requirements and experimental irrigation volume requirements for EPP 1.*

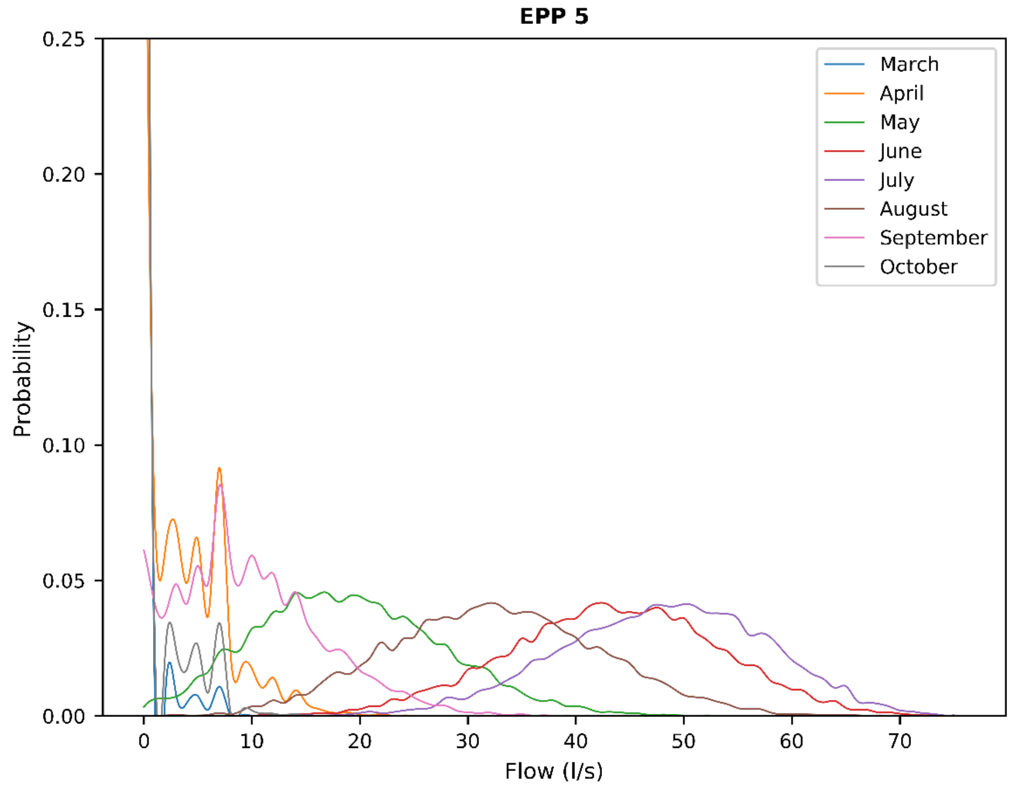

Figure 4-12. *Mass probability functions for the possible flow values during the irrigation season for EPP 5*

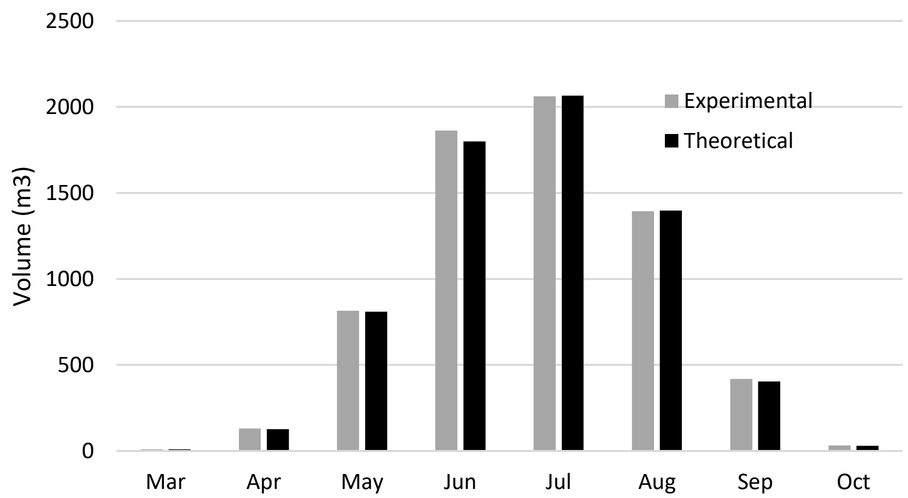

Figure 4-13. *Theoretical irrigation volume requirements and experimental irrigation volume requirements for EPP 5.*

4.4.4. PAT operating conditions analysis

Every experimental Q-H and PAT curve had to be defined. Every Q-H system curve was obtained from the hydraulic model. For the different EPPs, an average of 16 million experimental curves were tested per EPP using Equation (4.10). Calculating the intersection between every PAT curve and the system curve, the maximum flow allowed to run through each device was obtained in each scenario *l*. Once these maximum flows were defined, the space of (Q_{lmPAT}, H_{lmPAT}) for each PAT associated to each scenario *l* were also defined for each possible value of Q. The relative efficiencies that every pair of (Q_{lmPAT}, H_{lmPAT}) would produce in each PAT were calculated using Equation (4.13), depending on the BEP flow of each device. With all the flows and heads for which the PATs would operate under, and the relative efficiencies associated to these values, the power produced in each circumstance was estimated.

4.4.5. Economic viability

The cost associated to each scenario and every PAT evaluated was calculated using Equations (4.16), (4.17) and (4.18). To estimate the civil works associated to each scenario, Equation (4.19) was applied. Depending on the power, the percentage represented by the civil works varies from low values, close to 10% of the total installation cost for greater powers, up to high values close to 70% for lower powers.

For the five EPPs analysed in the network studied, the energy that would be recovered varies within the range [0.9 – 43.3], [2.4-6.9], [1.1 – 30.4], [0.5 – 11.2] and [0.4 – 5.6] MWh respectively. To calculate the annual revenues, several authors have used different values in their research. Perez-Sanchez et al. (2016) fixed a price of $0.0842\ €kWh^{-1}$, whilst García Morillo et al. (2018) applied the monthly average of the Spanish tariff based on 6-periods. In this case, the application LUMIOS (Red Eléctrica de España n.d.), developed by the Spanish Electrical Grid, which provides the monthly average tariff for a selected period, has been used to calculate the monthly tariff for the year 2017.

The values, in € kWh^{-1}, for the months in which energy is produced, were: April (0.111242), May (0.112542), June (0.113439), July (0.113044), August (0.113056) and September (0.113611). These tariffs were considered since the energy recovered has been assumed to be for self-consumption instead of selling it to the grid, as in many cases, there are no grid connection points close to the installation and it would be considered as saved energy. Thus, this connection could make the installation much more expensive, and was not considered as a viable solution for energy production in the irrigation sector.

Using Equations (4.21) and (4.22) to calculate the annual revenues and the payback period respectively for each scenario, and following the boundary conditions imposed for the payback period, the optimal PAT for each EPP was obtained, or the EPP was rejected. Thus, for the five EPPs, the summarised results can be seen in Table 4-4. Two of them were considered as viable individually for a PAT installation for energy recovery, two of them were rejected because of their PP exceeded 10 years, and one could be considered as potentially viable for being just in the border of the 10 years for returning the investment. These three EPPs would recover a sum of 81.4 MWh. Nevertheless, considering the five EPPs as a single investement, the PP would be 6.4 years, increasing the energy recovered up to 93.9MWh for the whole set.

The civil works, which were calculated following Equation (4.21), for the optimal solution of each EPP represented 43.5%, 58%, 50.3%, 53.5% and 58.2% of total cost, respectively.

Table 4-4. *Summary of the results obtained for each EPP and for the set, showing the optimal scenario, BEP flow, BEP power of the optimal scenario, number of polar pairs of the electromechanical device, total installation costs, energy recovered in the optimal scenario.*

EPP	Optimal Scenario	BEP Flow (l/s)	BEP Power (kW)	Polar Pairs	Cost (€)	Energy (MWh)	PP (years)
1	2,743,236	88	9.1	1	16,438	40.8	3.5
2	13	39	2.9	2	12,339	6.9	15.8
3	631,784	54	5.8	2	14,207	29.5	4.2
4	30,122,847	46	4.5	2	13,352	11.1	10.6
5	1,051,433	36	2.8	2	12,278	5.6	19.4
Total	-	-	**25.1**	-	**68,614**	**93.9**	**6.4**

4.5. Discussions

Flow fluctuations are very significant in irrigation networks, since the irrigation requirements vary along the irrigation season, depending on the crops. Furthermore, the farmers' irrigation habits are not standardized in on-demand irrigation networks. Due to the lack of, or difficulty to access data in this sector, one method to obtain the performance of the network is a statistical analysis based on the crop water requirements. Applying Clément's methodology and Bernoulli Experiments to an on-demand irrigation network, an estimation of the data along the network can be obtained. Characterising the network through their application makes the estimation of the flow fluctuations possible, approximating the monthly probability that each flow has of occurring and the probability to be exceeded. This analysis estimated the different values that could run through a specific pipe during the whole irrigation season. All of these flows have been evaluated as BEP flows simulating as many theoretical PATs as the number of flow values there were for each EPP. However only one machine can be selected for installation, and this methodology allows us to select a PAT whose BEP gives the best return on investment from all possible flow/head combinations across the irrigation season.

A limitation of this methodology is that a general PAT performance curve has been considered for all of the possible PATs that could be installed, underestimating in some cases and overestimating in others, the energy that could be recovered using each specific PAT studied. This general performance curve has been developed from the characteristic curves of 116 different PATs, extrapolating them and obtaining a general curve (Novara and McNabola 2018). Therefore, this methodology, applied the general PAT performance curve, helping to study all the possible scenarios for an energy recovery installation, pre-selecting the possible power outputs and choosing the best one regarding their payback period. However, a deeper investigation would be necessary in each EPP site once it is established by this methodology that the economic viability is predicted to be favourable.

Another limitation of the methodology is the fact that while many theoretical PAT BEPs were analysed among the possible combinations of flow across the irrigation season, a finite number of pumps exist in the market. The PAT curves were obtained using Equation (4.11), which is based on experimental data from 12 pumps tested as turbines (Barbarelli et al. 2017). In reverse, these pumps function as PATs and are considerably cheaper than traditional turbines due to mass production. Therefore, not every theoretical PAT is in existence in the marketplace and to retain cost competiveness, in practice we would need to select the closest available machine to the selected theoretical one for a specific EPP. The current methodology may under- or over-estimate economic viability at specific EPPs as a result of this limitation.

Regarding the domain of the random variable Q, formed by the number of possible combinations of downstream open and closed hydrants, it will be greater as the number of downstream hydrants increases. This means that the possible flow values will increase as the number of downstream hydrants does, having a larger probability of flow fluctuations as the quantity of hydrants increases. In the present case study, four of the EPPs had more than 20 hydrants downstream, where, > two million possible flows could occur.

The consideration of relative efficiencies in this study are very important. For the flow fluctuations, as their occurrence probabilities change significantly along the irrigation season, the energy that would be produced using other methodologies which just account for the energy recovered under BEP for average flows and heads, would not give realistic results. Thus, the variation of the PATs efficiency depending on the flow rate variation, allows a more realistic power output capacity to be installed in a specific EPP. Different variables could be considered when the viability of a PAT installation is being examined, such as the energy maximization. Nonetheless, if the variable to be maximised was the energy, then, the optimal scenarios would divert to higher BEP powers, where the PP would raise up to levels which could make the investment unviable. In spite of this, maximising the energy has been used in other research, and this methodology selects the best PAT for which the investment would be recovered the soonest. This would be more inviting for the farmers to install.

A comparison between the energy recovered in the scenario with the lowest PP and the scenario producing the greatest energy is displayed in Figure 4-19 (EPP3). The energy would increase up to 30.2MWh. This would amount to 2.3% more energy recovery. However, the PP would increase by 4.4%.

The civil works accounted for here differed from the civil works used by other authors. Some authors stated that 65% of the total installation corresponded to the cost of the PAT and the generator, and the other 35% was accounted for other works (Lydon et al. 2017b). In other cases, the civil works were considered to be around 25% of the total installation costs (Lydon et al. 2017a). Both considerations linked the civil work costs to the power to be installed and many previous papers were also not considering costs in the irrigation setting which differs in nature from urban constructions.

Nonetheless, for a random installation, the percentage of costs represented by civil works will change with the power. Thus, different power values of PAT for the same point will not vary the civil works to be conducted, but the percentage of these will change, being lower as the power increases. Therefore, for this research, an estimation of the general civil works to be carried out in these kind of installations in irrigation networks has been calculated, which contains general works and the main elements to be carried out. The result of this is a curve relating the power of the installation with the percentage represented by the civil works within the total costs of the installation. This gives a more realistic weight to the civil works than the previously used.

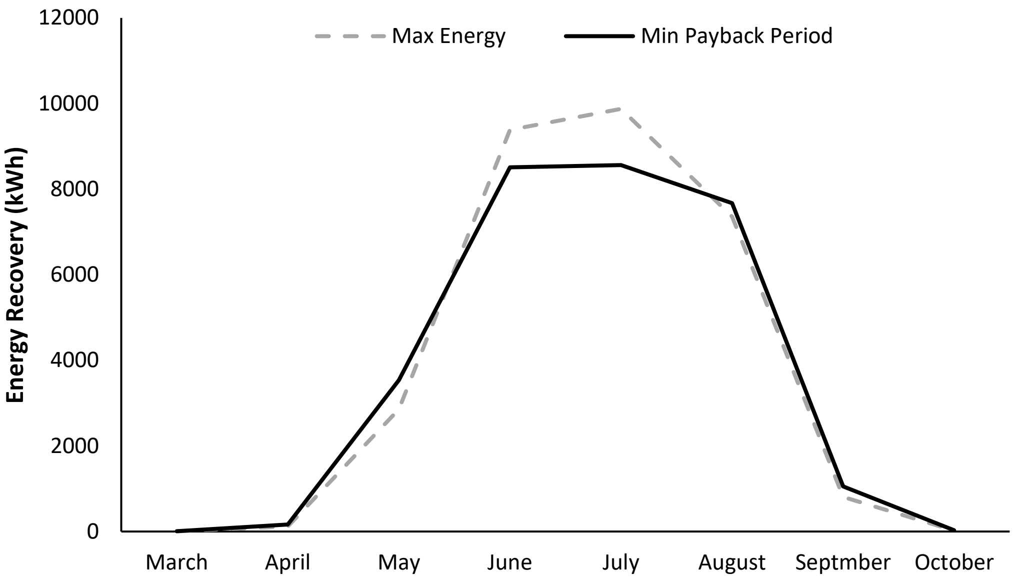

Figure 4-14. *Comparison between the most energy producing scenario and the lowest PP scenario in EPP3.*

The energy prices to be considered depend on the location of the irrigation network and energy use. In this case, the energy recovered has been considered to be auto-consumed by the farmers or the irrigation district itself. Hence, the energy recovered could be considered as a saving on the energy consumption.

The case studies pump station accounts for a power consumption of 1,080 kW. The power estimated to be potentially viable, was 25.1 kW. This amount represents 2.3% of the total power of the pump station. However, the power production of 25.1 kW represents the average power output across the year, where peak production of up to 45.8 kW would be reached in some stages of the irrigation season. The five PATs would be able to recover 93.9 kWh in an irrigation season. If the nominal power of the whole set is compared with the unitary pumps' power, the PATs' power amounts to 28.0% of the total power for the first type and 9.3% for the second type.

However, these points were found in remote place with no energy demand nor grid connection, far from the main consumption point of the irrigation district, the pumping station. The distance between the EPPs and the pumping station was at least of a few kilometres. The connection with the consumption points or the grid would importantly increase the cost of the plants, turning them in some cases not economically viable. This issue might be present in many nodes showing power potential in irrigation networks. Hence, deeper analysis should be carried out in feasibility studies for actual plants.

Depending on the stage of the irrigation season, the number of pumps working changes. Therefore, this could translate to an important energy saving in those stages where a lower number of pumps work. The index of the annual energy recovered per irrigated surface area was 0.10 MWh $year^{-1}$ ha^{-1}. This shows that the potential available in this specific network is not large. Previous investigations showed values of 0.65 and 0.08 MWh $year^{-1}$ ha^{-1} (García Morillo et al. 2018; Pérez-Sánchez et al. 2016). However, these values cannot be compared, since each index will partially depend on the topography in which the network is built. In addition, these previous estimates did not consider both flow variations and turbine efficiency variations and may therefore be over-estimates.

Finally, the application of MHP for energy recovery together with other potential energy saving measures proposed in other investigations would have a positive effect, reducing the energy dependency of the activity. For instance, the optimisation of pump stations would not remove the excess pressure in every area of a network. The excess pressure due to change in elevation among others would still exist, and therefore, the application of MHP would be a viable solution for both, reducing the excess pressure and energy dependency in the network.

4.6. Conclusions

In pressurized irrigation networks, energy reaches around 40% of the total water costs. The use of renewable energy sources in the agricultural sector will increase in the next few years. The percentage of crop water costs related to the energy comprise an important percentage of the total costs paid by farmers. In addition, the environmental pressure to reduce the greenhouse gases emissions will be a critical driver in this issue. PAT installations in these infrastructures have been shown as viable solutions to improve the sustainability and economic viability of this sector, due to their low cost in comparison with other technologies, as such traditional turbines in the case of hydropower, or solar and wind power in the case of €/kWh produced.

Reducing operating costs by this amount will result in lower food prices for consumers and potential for greater crop yields (avoiding deficit irrigation). As a result, the incorporation of MHP energy recovery in irrigation networks has an important role to play in the water-energy-food nexus, lowering GHG emissions, lowering food prices, reducing energy consumption and increasing crop yields.

This research develops a new methodology to optimise the PAT power to install at pre-selected sites in irrigation networks, where no data is recorded, minimising the payback period of the investment and combining combinatorial and statistical analysis. Three constraint conditions were fixed to achieve this goal. There can be no lack of pressure in the network after the installation with these constraints applied. The installation PP had to be lower than 10 years. Moreover, the scenario with the lowest PP was selected, whose power is the basis of the PAT selected.

The energy recovery for the set including the five EPPs, summed to 93.9 MWh. These energy savings estimated in this chapter could comprise important economical savings for farmers. Future works will study the validation of this methodology with actual measured data, and its use in irrigation networks where there is no access to actual data, to assess the potential available in this sector and the percentage represented by energy saved over the total energy consume

5 METHODOLOGY VALIDATION

5.1. Introduction

MHP has been shown as an attractive technology for reducing energy dependency in water networks where an excess pressure exists. A significant body of research has been conducted on this topic in recent years for drinking water networks, however limited attention has been given to its application in the irrigation sector. Using MHP, energy may be recovered at excess pressure points without affecting the water supply service (McNabola et al. 2014b). PATs were presented as cost effective devices for energy recovery in sites with the small power output capacities typical of this setting (Fecarotta et al. 2014b; Lydon et al. 2017a).

However, anticipating their performance is a well-known challenge (Novara and McNabola 2018). There are several methods to predict this performance, such as computational fluids dynamics (CFD), experimental testing, using the rotor-volute matching principle, geometry recreation or machine learning techniques (Barbarelli et al. 2016; Huang et al. 2017; Rossi et al. 2019; Rossi and Renzi 2018). Some authors (Barbarelli et al. 2017; Derakhshan and Nourbakhsh 2008; Fecarotta et al. 2016) have also proposed equations to predict the flow-head (Q-H) characteristic curve of PATs inputting the flow and head for which the device works with the highest efficiency, known as best efficiency point (BEP). These equations estimate the relative head depending on the flow rate. Flow variability has been shown as one of the crucial factors when selecting a PAT, since it will greatly affect the design point and operational efficiency of the selected device (Lydon et al. 2017b).

Flow fluctuations are generally more significant in irrigation networks, since the demand is normally concentrated in summer. This fact affects the viability of PAT installations directly for this purpose. Furthermore, it is not common to have detailed records for flow and pressure in irrigation networks, which makes the selection of a turbine more challenging as a result.

Subsequently, in the previous chapter a new methodology to select PATs for energy recovery at excess pressure points (EPPs), estimating the monthly occurrence probability for each possible flow value was proposed. The EPPs were located by running a hydraulic model of the network considering a set a percentage of hydrants to be open simultaneously and ensuring minimum pressure requirements in critical nodes. The excess pressure found using this analysis was fixed as the best efficiency head in each EPP. It also took into account both flow fluctuations and PAT efficiency performance variability, testing different theoretical PATs and choosing the one with the lowest payback period. The interaction between the predicted flow and recovered head PAT curves and the theoretical flow-head curve of the pipe system were also considered to define the range of flows that could be turbined, and the head that could be recovered.

This chapter presents the evaluation and validation of the methodology proposed in Chapter 4 as a method to quantify the existing power and the potential energy recovery in excess pressure areas within irrigation networks. Several statistical parameters and efficiency criteria were used to compare the results coming from simulations and from the application of actual flow and pressure observations in a real network, in high resolution, and over a 1-year period. The validation of this methodology will allow its application in different irrigation networks to quantify the existing potential and study how PATs could improve their energy efficiency. The accuracy of the method is also compared with previous approaches to demonstrate its improved effectiveness.

5.2. Methodology

Regardless of the different methods proposed to assess hydropower potential in irrigation networks, the evaluation of the performance of these models against measured data is required. To carry this out, efficiency criteria have to be used to measure how well the predicted observations fit with the measured field data (Beven 2012). The methodology validation was conducted using actual recorded flow data, comparing this with predicted experimental flow data and their occurrence probabilities along an irrigation season.

A statistical analysis of the flow domains was carried out, comparing the goodness of fit between predicted and actual values. Subsequently, theoretical PATs were simulated in the network using both, actual and predicted flow data, selecting the best solutions in each case in terms of minimising payback period. Among the output variables, the power generated under best efficiency conditions, the energy recovery potential, the best efficiency flows and heads, and the payback periods were used to analyse the accuracy of the predicted results. Different statistical parameters to measure error and goodness of fit of the model were calculated for the output variables.

Flow data was obtained from the Canal del Zújar Irrigation District (CZID), located in South-Western Spain. This district is composed of ten independent hydraulic sectors, and the data used corresponded to Sector II. This sector irrigates 2,691 ha, with tomato, maize and rice as the main crops, accounting for around 90% of the irrigated area. The network, comprised pipes with diameters between 80 and 1000 mm, supplying water to 196 hydrants. The hydrants were at levels varying from 250 m to 285 m. The network was designed to supply 1,2 l s^{-1} ha^{-1} on-demand (24 h per day), under the hypothesis of 100% of simultaneity (i.e. all hydrants simultaneously open). The service pressure required at hydrant level was 35m. The annual rainfall and evapotranspiration during 2015 summed to 202 mm and 1,372 mm respectively. A telemetry system was installed to record the hourly water demand through flow meters installed at the 196 hydrants during the 2015 irrigation season (González Perea et al. 2019). It is very uncommon to have this kind of system installed in irrigation networks and therefore access to this dataset presented a unique opportunity to perform this validation.

Grouping these water demands, the hourly flow running through each pipe of the network and the hourly volume pumped within the whole district, could be obtained. As highlighted earlier, recorded flow information at this level of spatial and temporal resolution is not commonly available in irrigation districts and thus this dataset provided a unique opportunity to validate PAT selection methodologies.

The methodology developed in the previous chapter consisted of the evaluation of MHP potential and PAT selection for pre-selected points in pressurised irrigation networks where no flow or head data was available. Due to the difficulty to find actual data in pressurised irrigation networks, this method predicted the flow and head distributions along an irrigation season inputting the crops distribution of each hydrant and the agro-climatic parameters (rainfall and evapotranspiration), to an EPANET hydraulic model of the network. Once the domains were defined, different theoretical PATs were simulated in the hydraulic model, following a simplified method of the variable operating strategy (VOS) (Carravetta et al. 2012; Fecarotta et al. 2016).

In this VOS, the flow and head ranges running through the turbine and the relative efficiencies were estimated depending on the flow rate, following two approaches: i) The characteristic flow-head drop curve of each PAT was defined following the model proposed by Barbarelli et al. (2017); ii) The relative efficiency was estimated following the model proposed by Novara et al. (2018).

A cost model was also included in the method, in which the total costs could be divided in: electromechanical devices costs, which included the PAT and the generator, following the cost model proposed by Novara et al. (2019); the civil works, which were defined for this kind of installations in irrigation networks specifically; and the electric cost that were defined as 20% of the total installation costs, following previous literature. Finally, the payback period was selected as objective function, choosing the PAT with minimum value for each point studied.

A limitation presented in the methodology was the fact of using a large number of theoretical PAT curves, which do not all necessarily correspond to an actual machine available in the market for purchase. The mass production of pumps makes them cost effective in reverse working as PATs and they are considerably cheaper than traditional turbines. Therefore, in reality, not every theoretical PAT can be found in the marketplace, and to retain cost-competitiveness in practice, the closest available machine to the selected theoretical one would need to be selected for a specific EPP. Thus, this limitation could lead the methodology to under- or over-estimate economic viability at specific EPPs.

This research was divided in different stages. Foremost, the characterisation of the flow fluctuations along the irrigation season was conducted, using both actual flow and predicted data at nine potential EPPs identified (as described below). The EPPs analysed can be seen highlighted on the skeleton of the irrigation network, shown in Figure 5-1. Next, the occurrence probability of each possible flow value was determined for both predicted and actual flow domains. Subsequently a hydraulic analysis was carried out applying previously calculated probabilities to estimate the energy recovery potential of every theoretical PAT simulated in the network. Finally, statistical parameters and efficiency criteria were used to check how good flows, energy and power variables fitted with their estimate using the measured data, providing more information on the model errors.

5.2.1. Excess Pressure Points

An EPANET (Rossman 2000) hydraulic model of the network was developed from several input files: i) A dwg file with the structure of the network; ii) database including the properties of the network (pipes, materials, diameters, consumption points, design properties, such as flow requirements in l/(s ha)); iii) Crops distribution for each hydrant; iv) and digital elevation model of the area to extract the nodes' elevation. With all this information, the model was developed.

Then, the model was validated comparing flows predicted by the model with the flows recorded distributions from a telemetry system. After, the excess pressure points were identified running the hydraulic model considering 100% of simultaneity (i.e. all hydrants open), as the network was designed for this hypothesis. In doing this, different branches of the network showed an existing excess pressure under these set conditions. Reducing this excess was conducted placing by PATs, such that the minimum service pressure was maintained in the network in these most unfavourable flow conditions.

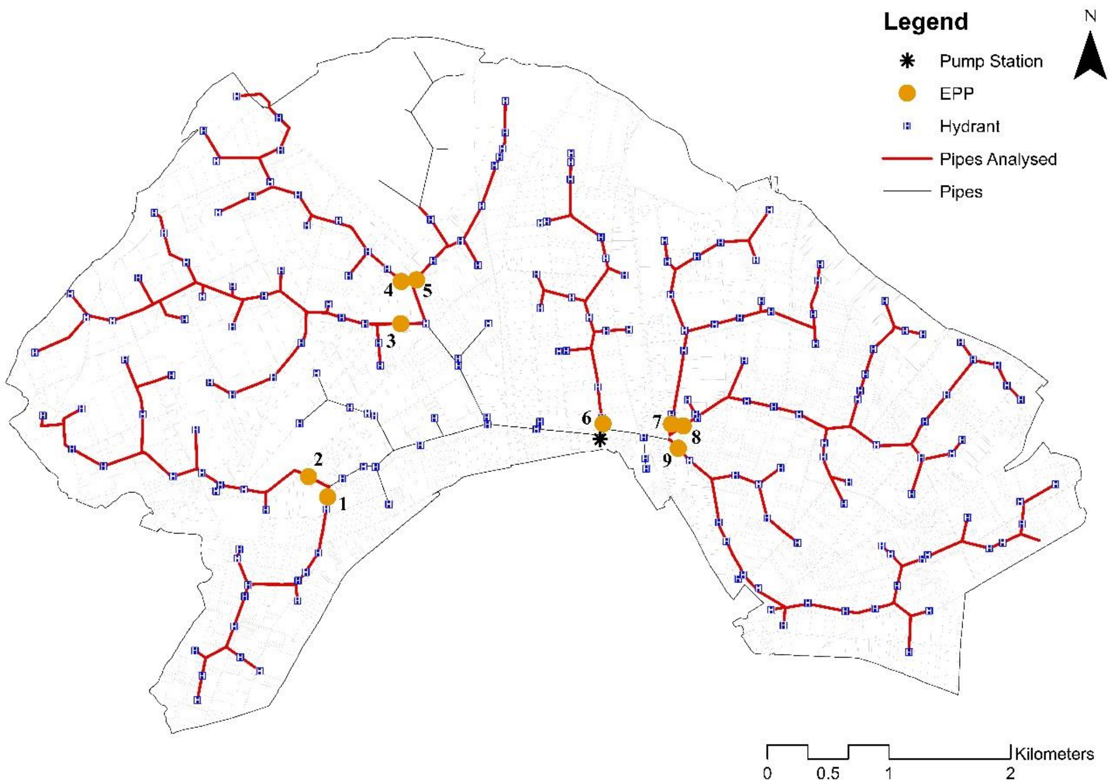

Figure 5-1. *Sector II of the Canal del Zujar Irrigation District skeleton and EPPs studied.*

The EPPs were fixed following two criteria: Minimising the existing excess pressure in the network to its service pressure, dividing the network into a set of hydrants with similar existing pressure; and to reduce pressure in as many hydrants as possible with existing excess pressure. This last consideration affected the working time of the PAT directly and, therefore the payback period, since the greater the number of hydrants downstream of a PAT, the lower the probability of null flow. This concentrated many of the flow values in a central range, increasing the energy recovery.

5.2.2. Flow fluctuations characterisation

The records gathered from the telemetry system reported the hourly demand of each hydrant. After the irrigation season, 860,832 values were registered. Therefore, the flow variability characterisation was conducted grouping all of the records of those hydrants located downstream of each EPP studied. Once grouped, the monthly occurrence probability of each flow was obtained. This occurrence probability was used to calculate the energy recovery for every flow demanded in every PAT. The predicted flow characterisation was carried out by running the Bernoulli Experiment as described in Chapter 4 and calculating the mass probability function. The Bernoulli Experiment was run integrating the EPANET engine into Python (v. 2.7.15) through its Dynamic Link Library. The occurrence probability of each flow was calculated following Equation (5.1):

$$p(Q_{ij}) = \frac{n_{ij}}{N} \tag{5.1}$$

Where n_{ij} represents the time that each value *i* was repeated in the month *j*; *N* is the number of observations in each case. For the actual data, the number of observations corresponded to the daily records (24) multiplied by the number of days in each month. In the prediction case, *N* was the number of simulations run.

5.2.3. Hydraulic Analysis

The methodology developed in Chapter 4 considered every flow running through an EPP as a possible best efficiency flow for a theoretical PAT. The best efficiency head was fixed as the minimum allowable head available to turbine downstream of each EPP for PAT selection. This allowable minimum was applied to ensure that the minimum service pressure was available downstream during the most intensive periods of irrigation. The head drop produced by the PAT for the maximum flow was thus fixed. Fixing this condition, a simplified VOS was applied, considering the PAT characteristic curve and the flow and head domains of the network. Then, as many PATs as different flow values obtained in the simulations or recorded in the network, were simulated in each EPP, with the previously defined best efficiency head and different values of best efficiency flows.

Once the actual and predicted flow domains were defined, the different PATs were simulated in the hydraulic model, applying both predicted and actual flow and head conditions. To simulate the different PATs in the network, the equations 5.2 and 5.3, which are described below, were implemented into the EPANET toolkit for Python, considering the flow distributions previously predicted. The flows and heads running through the turbine and the bypass were estimated for each PAT. Thus, every PAT showed a maximum flow that could be turbined, from which larger flows started being diverted using hydraulic regulation following the scheme proposed by Lydon et al. (2017a) (see Figure 5-2). The variations of flows turbined and head recovered were obtained through the interaction between the flow-head system values and flow-head drop PAT curve. The head drop values were calculated depending on the flow rate, following the Equation (5.2), proposed by Barbarelli et al. (2017). The relative PAT efficiency for each flow demanded was obtained using the flow rate-relative efficiency equation proposed by Novara and McNabola (2018), Equation (5.3). The power produced depending on the flow rate was also calculated depending on the flow rate, relative head drop and relative efficiency, following Equation (5.4). The energy recovered by each PAT was calculated applying both predicted and actual occurrence probabilities during the irrigation season. Finally, the PAT selected in each case, presented the lowest payback period. A sample of the results of this process is shown later in this paper chapter in Figure 5-2. Finally, the specific speed was calculated following the Equation (5.5), considering a nominal speed of 1500 rpm.

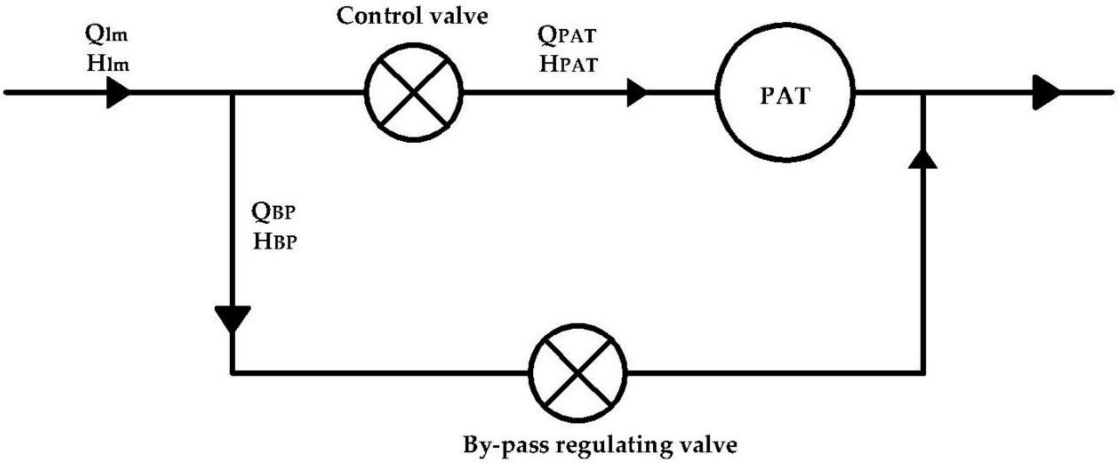

Figure 5-2. *PAT installation scheme with hydraulic regulation*

$$\frac{H_i}{H_{BEP}} = 0.922\left(\frac{Q_i}{Q_{BEP}}\right)^2 - 0.406\left(\frac{Q_i}{Q_{BEP}}\right) + 0.483 \tag{5.2}$$

$$\eta_i = 0.5197\left(\frac{Q_{iPAT}}{Q_{BEP}}\right)^3 - 2.3328\left(\frac{Q_{iPAT}}{Q_{BEP}}\right)^2 + 3.0931\left(\frac{Q_{iPAT}}{Q_{BEP}}\right) - 0.2757 \tag{5.3}$$

$$P_i = 0.55\ Q_{iPAT}\ H_{iPAT}\ \gamma\ \eta_i \tag{5.4}$$

$$N_S = \frac{N\sqrt{Q_{BEP}}}{H^{0.75}} \tag{5.5}$$

5.2.4. Statistical analysis

The methodology aimed to predict irrigation network flow fluctuations to enable the selection of the PAT with the lowest payback period. Thus, the variables used for the statistical analysis of the performance of this methodology were: from one side, the flow values, and from the other side, the variables related with the PATs performance, such as power, energy recovery and BEP.

In this stage, different parameters were used to measure the statistical significance of differences between the results obtained applying predicted and actual data. The mean absolute error (MAE) and the root mean square error (RMSE), both expressed in the same unit as the variable studied, were used to quantify the differences between the predicted and observed values. The efficiency of the model was also measured calculating the coefficient of determination (R^2), and Nash-Sutcliffe model efficiency (E). Low values of MAE and RMSE show a better fit of the model.

The coefficient of determination is widely used in the analysis of quality of regression and prediction models, and is a measure of precision. It is defined as the squared value of the coefficient of correlation according to Bravais-Pearson (Krause et al. 2005). The Nash-Sutcliffe model efficiency (*E*) estimates how well a simulation can predict an outcome variable. As well as the R^2, a value of zero for *E* represents no correlation, and 1 that predicted values are equal to the observed. These parameters can be calculated using Equations (5.6), (5.7), (5.8) and (5.9).

$$MAE = \frac{\sum_{i=1}^{n} |\hat{y}_i - y_i|}{N} \tag{5.6}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (\hat{y}_i - y_i)^2}{N}} \tag{5.7}$$

$$R^2 = \left(\frac{\sum_{i=1}^{n} (y_i - \bar{y})(\hat{y}_i - \bar{\hat{y}})}{\sqrt{\sum_{i=1}^{n} (y_i - \bar{y})^2} \sqrt{\sum_{i=1}^{n} (\hat{y}_i - \bar{\hat{y}})^2}} \right)^2 \tag{5.8}$$

$$E = 1 - \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} \tag{5.9}$$

Where $\boldsymbol{\hat{y}_i}$ is the value of the variable using the predicted data; $\boldsymbol{y_i}$ the value of the variable analysed with the observed data; *N* is the number of observations; $\boldsymbol{\bar{y}}$ is the mean value of the values obtained using observed data; $\boldsymbol{\bar{\hat{y}}}$ is the mean value of the results obtained with the predicted data; and n is the number of observations in the sample in each EPP.

A comparison between PATs obtained under predicted and actual conditions was carried out when both worked under actual conditions. This was conducted to see if the differences in flow values obtained between the predicted and measured data, made a substantial difference to the energy produced by PAT designs based on the predicted data or based on the actual measured data. Differences in flow data may not translate into the same difference in energy production. The energy recovery was analysed, studying the differences found between the total amount found in the network and the amount found in each of the EPPs.

5.3. Results

The predicted and actual flow fluctuations of the nine EPPs chosen were calculated along the irrigation season. The actual flow fluctuations were obtained from 4392 hourly data entries registered in each hydrant located downstream of each EPP from the April 1 to September 30, during the irrigation season in 2015. Grouping these entries, 4,392 flow values were obtained for each EPP. Using these records, the actual occurrence probability was calculated for each flow value. To obtain the experimental variability, the combinations of open/closed hydrants downstream were calculated for each EPP. Monthly simulations were run for at least twice the number of possible combinations of open/closed hydrants downstream of each EPP site. Table 5-1 shows a summary of the information used to calculate the flow fluctuations and occurrence probability for actual and predicted values in the nine EPPs, accounting for almost 10 billion simulations. In Figure 5-3, a comparison between the predicted and actual occurrence probability of every flow is presented, for four of the nine EPPs analysed.

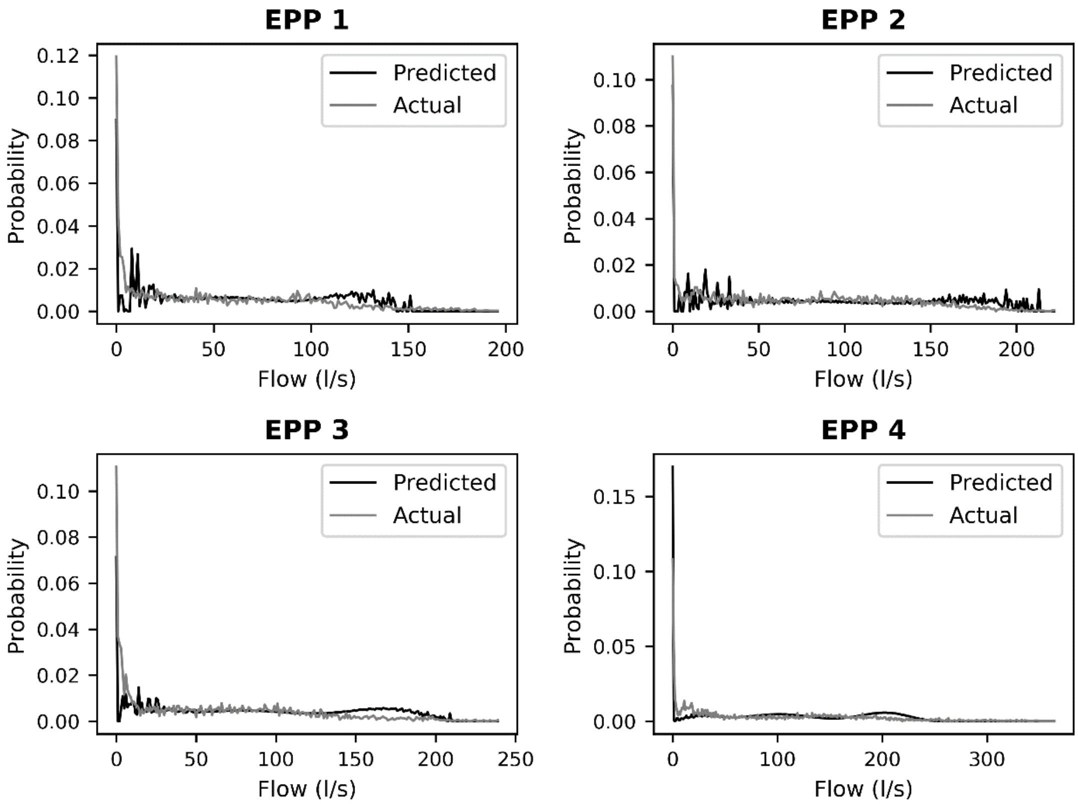

Figure 5-3. *Predicted and actual occurrence probabilities for the different flow values along the irrigation season in four of the nine EPPs studied.*

With the flow domains characterised, different PATs were simulated considering these fluctuations. A finite number of PATs simulated in one of the EPPs, together with the selected PAT and its power production, can be seen for illustration of this process in Figure 5-4. The black line represents the branch flow-available head curve. The horizontal dashed line is the best efficiency head, fixed as a boundary condition in the methodology. The coloured dashed lines are the flow-head recovered curves of the theoretical PATs simulated (205 PATs in this case).

The thickest line in blue represents the selected PAT with the lowest payback period. The red thick line represents its corresponding power production under each flow demanded. Its power production starts decreasing when the flow demanded is greater than the maximum flow to be turbined. Thus, the flow is diverted and the amount of flow turbined is lower when the demanded flow increases. The working conditions of the PAT installation were fixed in order to always have sufficient pressure in all of the hydrants. To ensure this, the interaction between the system and the PAT curves in the methodology, it was introduced in the previous chapter. The different characteristic curves for predicted conditions together with the specific speed of each, can be seen in Figure 5-5.

Table 5-1. *Number of downstream hydrants, number of entries used to obtain the flow fluctuations, observations to obtain the actual occurrence probability and the number of simulations run in each EPP.*

	Hydrants downstream	**Flow entries**	**Actual observations (N)**	**Simulations (N)**
EPP1	15	65,880	4392	393,216
EPP2	14	61,488	4392	196,608
EPP3	23	101,016	4392	100,663,296
EPP4	14	61,488	4392	196,608
EPP5	10	43,920	4392	12,288
EPP6	18	79,056	4392	3,145,728
EPP7	18	79,056	4392	3,145,728
EPP8	29	127,368	4392	6,442,450,944
EPP9	28	122,976	4392	3,221,225,472
Total	-	742,248	-	9,771,429,888

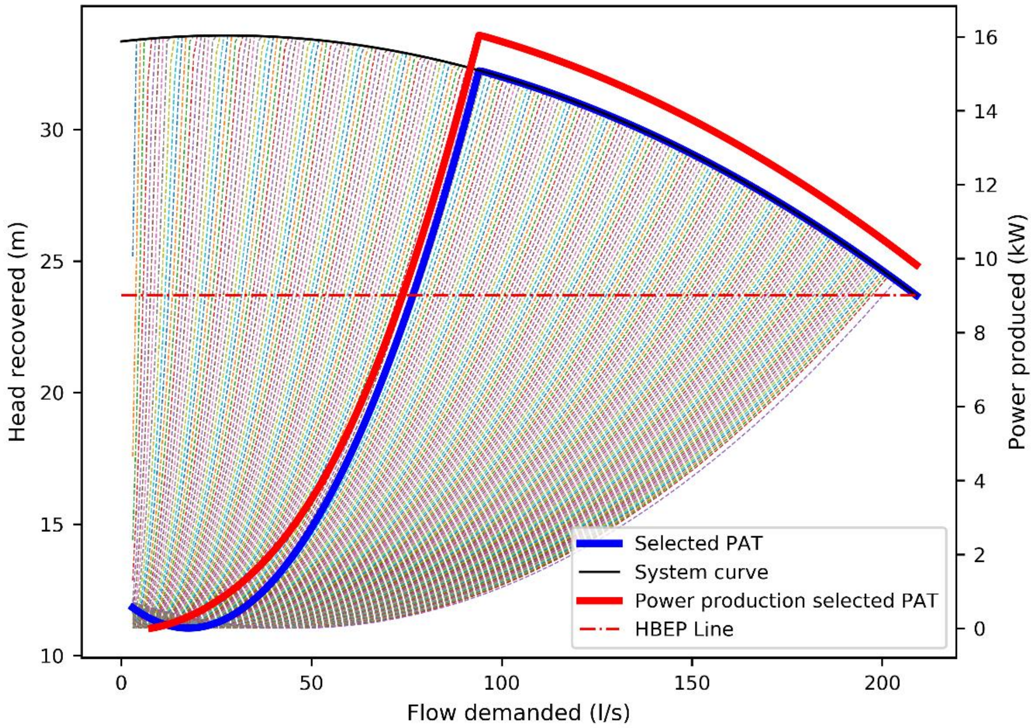

Figure 5-4. *205 experimental PATs simulated in the EPP3, the system flow-available head curve, the selected PAT flow-head recovered curve, the power generated under each demanded flow and the best efficiency head line.*

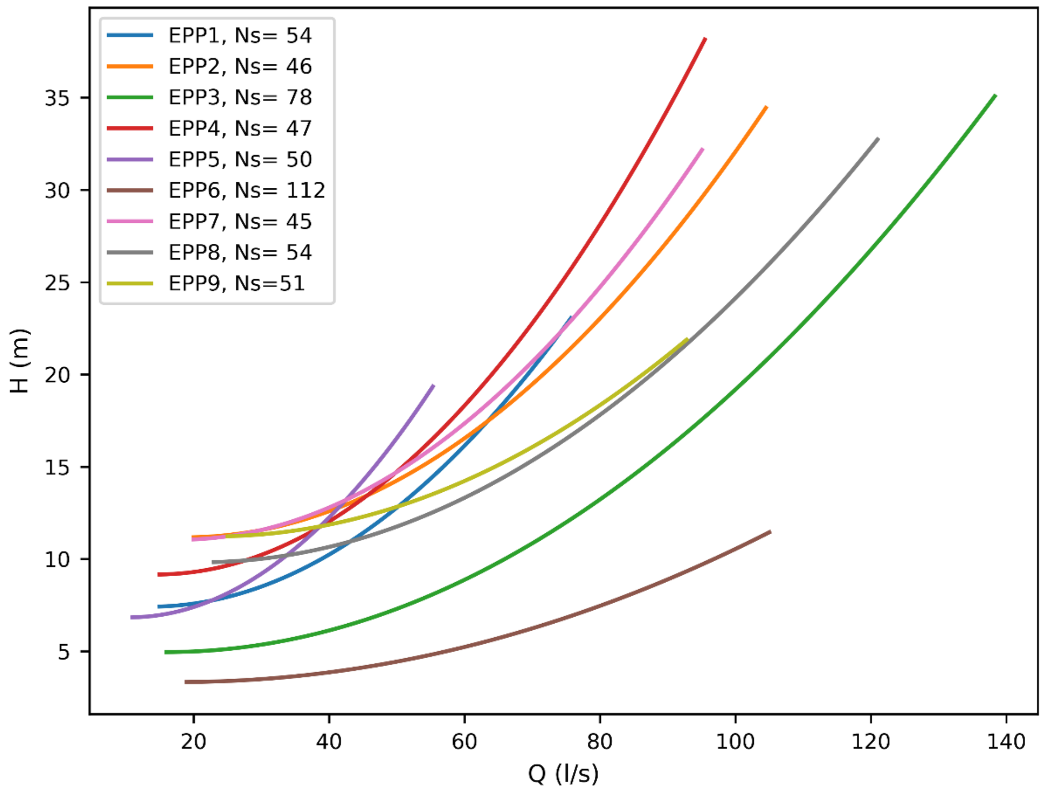

Figure 5-5. *Nine characteristic curves and specific speed for the PATs selected for predicted conditions.*

Statistical analysis was carried out to validate the predictions of the methodology from different perspectives. Firstly, the goodness of the fit was analysed between the predicted and actual flows for the nine EPPs identified. Second, the goodness of fit was also analysed between the power, energy and BEP for predicted and actual PAT performance. Finally, a comparison was made of the performance of the predicted PAT operating under the actual flow conditions.

The values for the different statistical parameters for every EPP can be seen in Table 5-2 comparing actual and predicted flow occurrence probabilities. The result for MAE and RMSE of the occurrence probability on average resulted in values of 0.0026 and 0.0068 respectively, what would suppose a difference of 11.4 hours and 29.9 hours during the irrigation season. The parameters analysing the model efficiency yielded 0.804 for the coefficient of determination and 0.576 for the efficiency criteria. The nominal power, potential energy recovery and BEP of the best solution obtained with the predicted flows and the actual records, can be seen in Table 5-3 for each of EPP. In Table 5-4, the statistical parameters calculated to compare these variables considered are also shown.

A total power of 72.8 kW and 68.2 kW were obtained when the methodology was applied with predicted and actual flows respectively. Regarding the energy recovery, these values were 281.0 MWh and 230.5 MWh respectively, with an energy recovery potential per unit irrigated area of 0.104 MWh ha^{-1} and 0.086 MWh ha^{-1} respectively.

The analysis of PATs obtained under predicted and actual conditions, both working under actual conditions, showed quite close results of energy recovery for both cases. The total energy recovery found when the PATs obtained for predicted conditions were simulated under actual conditions was 229.9 MWh. The average error found was 3.9% for each EPP, with an error of 0.2% when the total energy recovery was compared. A summary of these results can be seen in the Table 5-5. Therefore, the impact of the errors in flow prediction is reduced when PAT performance is considered due to the wide variety of the machines characteristic curve taken into account.

Table 5-2. *Summary of the statistical parameters values obtained for each EPP comparing predicted and actual flows' occurrence probabilities.*

	MAE	**RMSE**	**R2**	**E**
EPP1	0.0028	0.0056	0.79	0.65
EPP2	0.0022	0.0033	0.92	0.81
EPP3	0.0016	0.0072	0.74	0.42
EPP4	0.0033	0.0122	0.86	0.55
EPP5	0.0049	0.0110	0.89	0.73
EPP6	0.0026	0.0073	0.72	0.50
EPP7	0.0023	0.0050	0.81	0.62
EPP8	0.0018	0.0044	0.71	0.44
EPP9	0.0019	0.0048	0.80	0.46
Average	0.0026	0.0067	0.80	0.58

Table 5-3. *Results obtained for predicted flow ($\hat{y}_i$) and actual flow (y_i) distributions.*

EPP	**Power** (kW)		**Energy** (MWh)		**BEP Flow** ($l\ s^{-1}$)		**BEP Head** (m)		**Payback** (years)	
	$\hat{y}_i$	y_i	$\hat{y}_i$	y_i	$\hat{y}_i$	y_i	$\hat{y}_i$	y_i	$\hat{y}_i$	y_i
1	5.7	5.7	19.0	16.3	62	62	16.9	16.9	6.7	7.8
2	11.4	7.8	41.0	34.6	83	69	25.5	21.0	3.7	3.9
3	4.4	6.6	37.8	40.0	72	87	11.3	14.1	3.3	3.4
4	7.5	10.5	34.3	25.9	66	63	20.9	31.0	3.9	5.4
5	4.1	4.1	10.5	8.0	48	45	15.6	16.9	11.3	14.9
6	3.3	2.8	12.5	8.5	81	72	7.6	7.1	9.7	13.7
7	11.0	8.3	36.1	27.4	81	66	25.2	23.2	4.1	4.9
8	11.0	7.8	47.4	34.7	95	85	22.4	17.0	3.3	4.0
9	14.4	14.7	42.4	35.1	104	111	25.6	24.5	3.9	4.7

Table 5-4. *Average value of statistical indices for the output variables.*

	Power (kW)	**Energy (MWh)**	**BEP Flow (l/s)**	**BEP Head (m)**	**Payback (years)**
MAE	1.73	6.10	8.78	3.08	1.44
RSME	0.74	2.32	3.49	1.43	0.65
R2	0.72	0.90	0.90	0.65	0.98
E	0.55	0.62	0.65	0.56	0.77

Table 5-5. *Energy recovery potential of PATs obtained under predicted and actual conditions when both were simulated under actual conditions*

EPP	1	2	3	4	5	6	7	8	9	**Total**
Actual (MWh)	16.2	34.6	40.0	25.9	7.9	8.5	27.4	34.7	35.1	230.4
Predicted (MWh)	16.2	36.6	35.7	26.6	7.9	8.7	28.5	36.2	33.5	229.9
Difference (%)	0.4	5.8	10.8	2.7	0.1	2.2	4.0	4.3	4.6	0.2

5.4. Discussion

The variations of flow and head have been presented as determinant parameters when selecting a PAT for energy recovery. The difficulty to find actual flow records in irrigation networks makes the generation of this data necessary when studying their existing hydropower potential. The existence of a recording system registering data with the grade of detail found in this network is very uncommon. It is more likely to find systems recording the total volume consumed in the whole irrigation season or periodic volumes to adjust the payment for the water consumed of each farmer. This fact makes the design of MHP plant for energy recovery quite difficult, since just the yearly volume used could be found, but no flow values. Nonetheless, the existing trend towards modernization in irrigation will lead to more installation of systems recording data with a higher grade of detail over time. Just under 10 billion simulations were conducted here to predict the flow fluctuations in all nine EPPs. Due to memory constraint, these simulations were split in different stages for those EPPs with a greater number of combinations, requiring more than two months to predict the flow domains for the nine EPPs. The results obtained showed a slight difference between the domains of the actual and predicted flows.

The actual data domain was generally slightly greater, as can be seen in Figure 5-2, since the existing excess pressure allows the farmers to have greater demands than the original network design limits of 1.2 $l\ s^{-1}\ ha^{-1}$, if required. This can be seen in the largest flow values of each EPP, where the predicted probability is zero but the actual flow has a small occurrence probability. In addition to this difference in domain size, the predicted flow domain concentrates higher occurrence probabilities in the extreme values. This difference is due to the excess demand compared to the design hypothesis. As the network is designed to supply water on-demand, an excess may occur at some hydrants, allowing greater demands at them in low intensive irrigation periods. Furthermore, EPANET is not a pressure-driven model, not allowing demand variations at consumption points depending on the available pressure. To take this variation into account, an EPANET toolkit based application should be developed. However, another key aspect would be missing; the farmers' irrigation habits, which are crucial to obtain the demand excess. Despite finding an actual greater demand than the theoretical, for most of the values in the different EPPs, the variation of the probability is not high, presenting a maximum difference value lower than 0.7%.

The main aim of this research was to validate the selection of PATs, based on the flow variations mentioned. Thus, after applying the hydraulic method proposed by in the previous chapter, inputting actual and predicted flows, the nominal powers of the PATs presenting the lowest payback periods were selected, and the potential energy recovery was determined. The results obtained when applying actual and predicted data showed a good fit between both results. Firstly, the analysis carried out in flow domains showed good results for the predicted values when compared to the recorded ones.

Analysing the MAE and RMSE, both presented maximum values in the EPP5, of 0.0049 and 0.0110 respectively. However, the values obtained in the other eight EPPs were significantly lower. Average values for the nine EPPs of 0.0026 and 0.0068 were obtained. These values measured the difference in the occurrence probability of each flow, where smaller values indicate a smaller difference between them. Analysing the hydrants downstream, EPP5 has the lowest number of hydrants; 11, while the average for the other eight EPPs is 20. This fact has impact on the number of open/closed hydrants combinations, and hence in the flow domain. For lower number of hydrants, the number of possible flows decreases, and thus their occurrence probabilities and vice versa. Therefore, the model seems to be more accurate when it is applied in pipes with a higher number of hydrants. Regarding the efficiency criteria used, maximum and minimum R^2 of 0.92 and 0.71 were obtained in the EPP2 and EPP8 respectively. The model efficiency E presented a maximum value of 0.81 and 0.42 of minimum. EPP2 presented the most accurate metrics, as the maximum flow actually demanded just exceeded 4% the design demand, being 222 l s^{-1} and 213 l s^{-1} respectively. Regarding the EPP8, the fact of returning the lowest efficiency criteria values seems to be related to the farmers' irrigation habits. The greatest difference was found in high flow values, more specifically within the range 200-250 l s^{-1} (see Figure B1-8 in Appendix B), where the predicted flows curve showed a greater occurrence probability, whilst the actual flows curve presented a lower probabilities values for the specified range. Thus, it appears to be more unlikely that farmers downstream the EPP8 irrigated at the same time, which had a direct impact on both metrics. The average values for the nine EPPs for both criteria were 0.80 and 0.58 respectively. From these values, and the small difference found in the errors, it could be surmised that predicted and actual flows, and their probabilities, presented a good fit.

The methodology validated in this research selects PATs with the minimum payback period for pre-selected locations. It would be interesting to implement this into the methodology of an optimisation algorithm to obtain the optimal location of points to install turbines as well as the optimal machine to select. To do this, the flow fluctuations would need to be predicted for each pipe of the network. Thus, it would be necessary to consider every possible combination of open/closed hydrants in the network.

Considering that there are 191 hydrants in the current case study, the number of combinations of open/closed hydrants would raise up to 3.2 million x 10^{51}. This fact would lead to a very large number of simulations and computational time, which cannot be afforded by normal computers. To make both algorithms work together, some variables would need to be limited. However, the application of optimisation algorithms for optimal locations together with PATs selection could be implemented when actual data is available, thus avoiding the computational time used for flow and head prediction.

The output variables, such as nominal power, potential energy recovery, BEP and payback period, were obtained running the hydraulic analysis with predicted and actual data. Four of the EPPs presented differences in the nominal power lower than 1 kW, obtaining an average MAE and RMSE for the nine EPPs of 1.73 kW and 0.75 kW. The total power obtained with predicted conditions accounted for 72.8 kW, differing by 5.6 kW from the power obtained under actual conditions (68.2 kW). Thus, the power obtained with predicted conditions was 8.2% greater. This fact shows very small differences between the power obtained when the methodology was run inputting predicted and actual flows and heads. The potential energy recovery presented an average MAE and RMSE of 6.10 MWh and 2.32 MWh respectively. The total energy recovery estimated under actual conditions summed to 230.5 MWh, raising up to 280.9 MWh for predicted conditions. In this case, the difference was 22%. The committed error per unit irrigated area for the nominal power and energy recovery potential was 0.0017 kW ha^{-1} and 0.0187 MWh ha^{-1} respectively. These values may be useful as a calibration of potential future research findings using this methodology.

The PATs resulting from the predicted and actual data were also compared. The BEPs were usually different, which affected their efficiency depending on the flow demanded, and so too their power generation. This fact is because of a combination of circumstances. Firstly, the greater demands mentioned before affected the available head in the system. In addition, the actual irrigation volume registered was 24.9% lower than the theoretical required value. This is a common practice (deficit irrigation), and the value is within the general range registered, which explains the differences found in the potential energy recovery in both cases. Rodríguez Díaz et al. (2011) used the Relative Irrigation Supply (RIS) index, defined as the ratio of the total annual volume of water diverted or pumped for irrigation and the theoretical crop irrigation requirements, to show these differences. The values found varied between 0.24 and 0.96, showing deficits varying between 4% and 76%. They concluded that deficit irrigation is a common practice for extensive field crops in this region. In this particular case (Zujar), the RIS index found was 0.75.

The best efficiency flows presented an average MAE of 8.8 l s^{-1}. This fact could affect the PAT behaviour, particularly for those PATs with a small best efficiency flow. For greater values, this would not be that significant, as the relative percentage represented by the MAE would be lower. Hence, the performance of the PATs obtained with predicted flows were also studied under actual flow conditions. With this test, the power production and the total energy recovered by both set of PATs could be analysed and compared.

This comparison for EPP7 can be seen in Figure 5-6. The power production is lower for the PAT obtained inputting actual flows, since its BEP was lower. The difference in the power production was around 1.1 kW for every flow, having a peak of difference of 2.7 kW when 97 l s^{-1} were demanded. However, the total energy recovery was very similar when both PATs were simulated under actual flow conditions. It was estimated that the PATs obtained with predicted flows would recover 229.94 MWh, while the ones obtained with actual conditions would recover 230.42 MWh. The small difference between both PATs working under actual conditions (≈0.48 MWh) shows that although the PATs obtained in the predicted and actual cases are different, the energy recovery would be very similar.

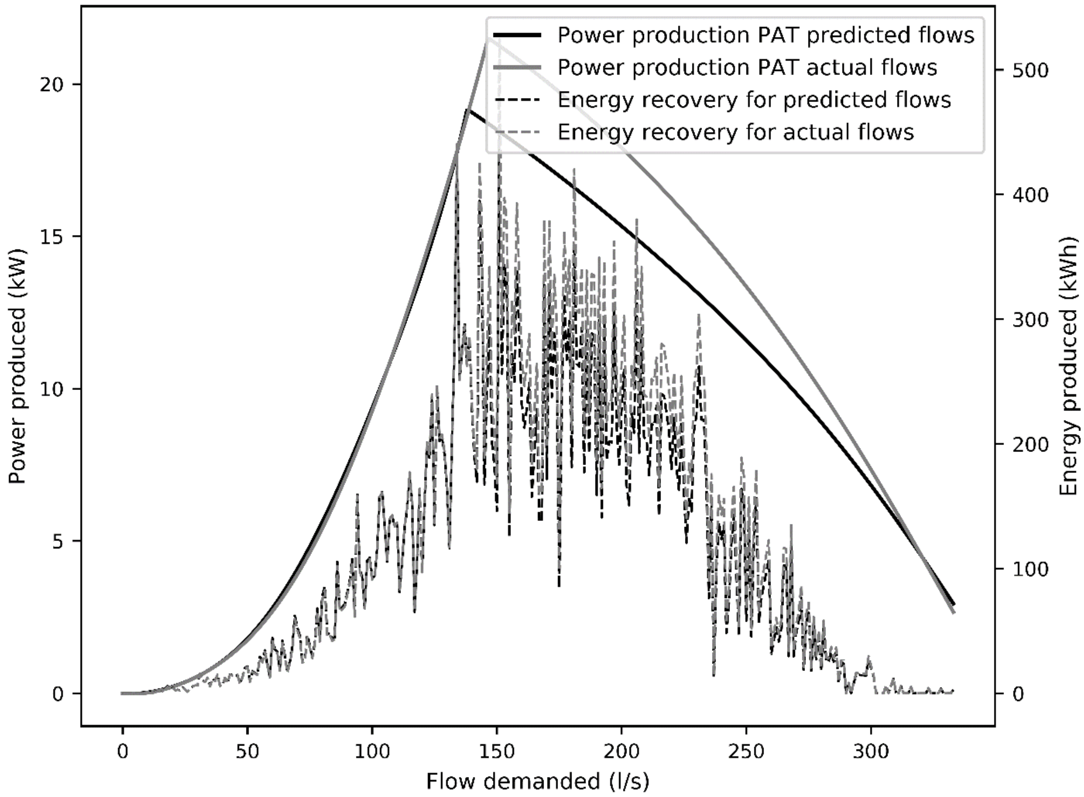

Figure 5-6. *Comparison between the power production and energy recovery by the PATs obtained under predicted and actual conditions, both running under actual conditions.*

From this fact, it can be highlighted that the methodology provides a PAT that would recover practically the same amount of energy in real conditions as the PAT resulting from the analysis run under real conditions. An overall difference of 0.2% over the total energy recovered in the network and an average of ± 3.9% in the points analysed were obtained from this analysis. In addition, it can be seen in Figure 5-6 how the energy recovery under each flow demanded is similar for both PATs. This fact highlights the importance of having precise and clear flow fluctuations defined, since the occurrence probability of each flow is going to influence the total energy recovery.

The importance of the number of simulations run was also evaluated, comparing the results obtained when different percentages of the theoretical simulations proposed in Chapter 4 were run. Seven different scenarios with different percentages of the theoretical simulations were run five times each. Namely 1%, 5%, 10%, 30%, 50%, 70% and 100%. The results for energy recovery potential showed a large dispersion and greater cumulative errors in those cases where the percentage of simulations were smaller. The dispersion and errors decreased as the number of simulations increased. The cumulative error for 1% of the simulations run was ±1.90 MWh, while for 100% of the simulations it decreased up to 0.15 MWh in EPP5.

The results obtained for the different scenarios in EPP5 can be seen in Figure 5-7, where the red dashed line represents the energy recovery potential obtained after applying the methodology for the first time in EPP5, and the triangles are the results obtained for each time that the different percentage of simulations were run. The cumulative error for each of the cases is also highlighted. From Figure 5-7, it can be seen how important the number of simulations to run are depending on the combinations of open hydrants. If the number of combinations is too high and the number of simulations run is too low, the error committed in the flow prediction will lead to larger errors in the output variables analysed (i.e. energy recovery potential).

A comparison between the results obtained from the methodology developed in this thesis and analysed in this chapter, and the results obtained when some assumptions were adopted from previous alternative approaches was also carried out. These assumptions included: i) taking average network flows and constant PAT efficiency; and ii) considering flow variations but assuming constant PAT efficiency.

Firstly, average flows from the simulations and constant efficiency were considered. The output power resulted in 82.9 kW, 14% greater than the power obtained using the current methodology, and 21% greater than the actual conditions. Nonetheless, the energy recovery potential dropped to 174.8 MWh, 38% less, raising the average payback period by 71%.

Despite the power potential obtained being greater, the average flows were greater than the best efficiency flows obtained in this methodology, and the energy recovery was therefore much lower leading to a higher payback period. The main reason to explain this difference lies in the cumulative occurrence probability. As the average flow was greater than the best efficiency flow obtained in this methodology, its cumulative occurrence probability was lower, since it decreases as the flow increases, steering to a shorter working time. Therefore, although the nominal power result was greater, the working time of the PAT when considering average flows was lower, reducing the energy recovery.

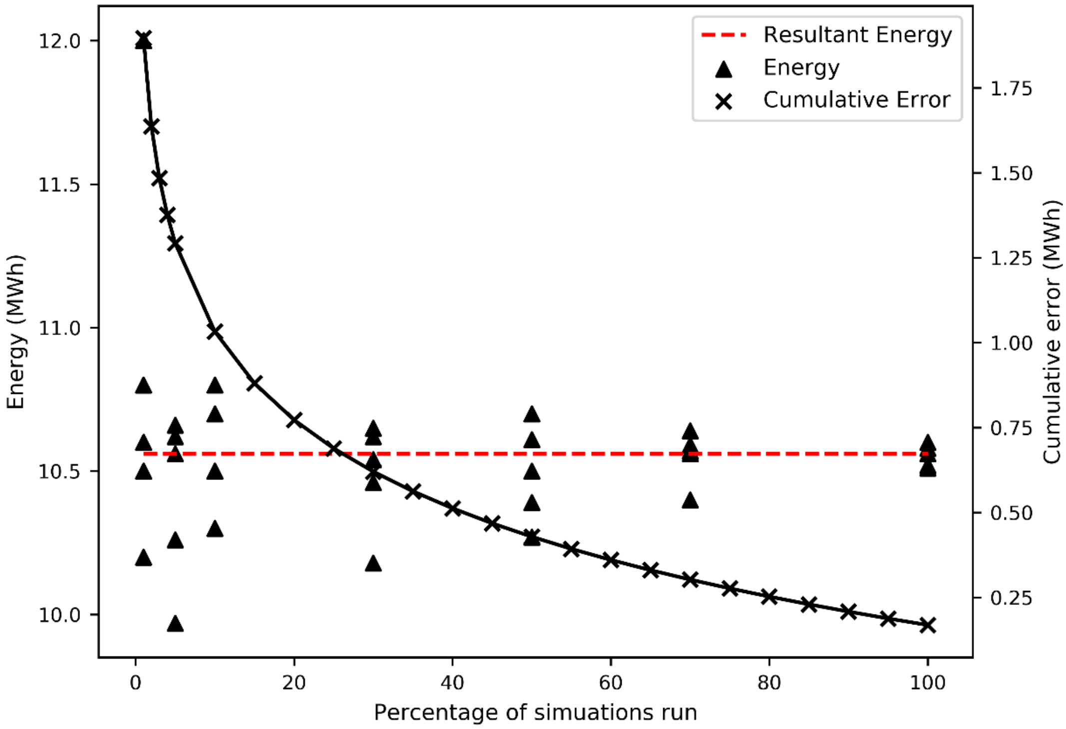

Figure 5-7. *Results obtained after running the methodology running different percentage of theoretical simulations compared to the result obtained after applying the methodology for the first time, showing the cumulative errors obtained for each scenario.*

The methodology was then applied considering variations on flows and heads, but keeping the PAT efficiency constant. The output power potential was 77.1 kW and the energy recovery 301.8 MWh, being 6% and 7.4% greater than the results obtained when considered variations on the PAT performance. The payback period was 6% lower on average. This assumption resulted in an overestimation of the power and the energy recovery potential, due to the performance of the PAT being kept constant independently on the flow rate. Nevertheless, previous research focused on PAT performance highlighted the importance of flow variations on the variations of PAT efficiency. Thus, it is unrealistic to consider constant efficiency, since the results obtained could show greater potential than the existing one.

Finally, an analysis of the pressure available in the most critical hydrant of each EPP of the actual system was also carried out, simulating the PATs obtained under predicted flows in the network, but working under actual conditions. With this test, it can be observed how these PATs can affect network functionality. Comparing actual conditions of the network and conditions after simulating the PAT, it can be seen how the pressure was considerably reduced, particularly in those months where the peaks in demand were concentrated (see Figure 5-8). Furthermore, it can also be seen how the by-pass system would work during these months (difference between grey continuous line and blue dashed line). In those months with lower demands, the flow demanded is completely turbined, since there is sufficient pressure in the system compared to the pressure recovered by the PAT for such flows.

It is also interesting to analyse how the pressure behaves for those flow values where the by-pass starts working to ensure the minimum service pressure. From this fact, two main points can be extracted: the interaction between the PAT and the system curves considered in the methodology is fulfilled and the service pressure is ensured. The results obtained from this analysis showed an average pressure reduction of 35% during the whole irrigation season, raising up to 42% in those periods where greater demands are concentrated, obtaining a maximum pressure reduction of 50%.

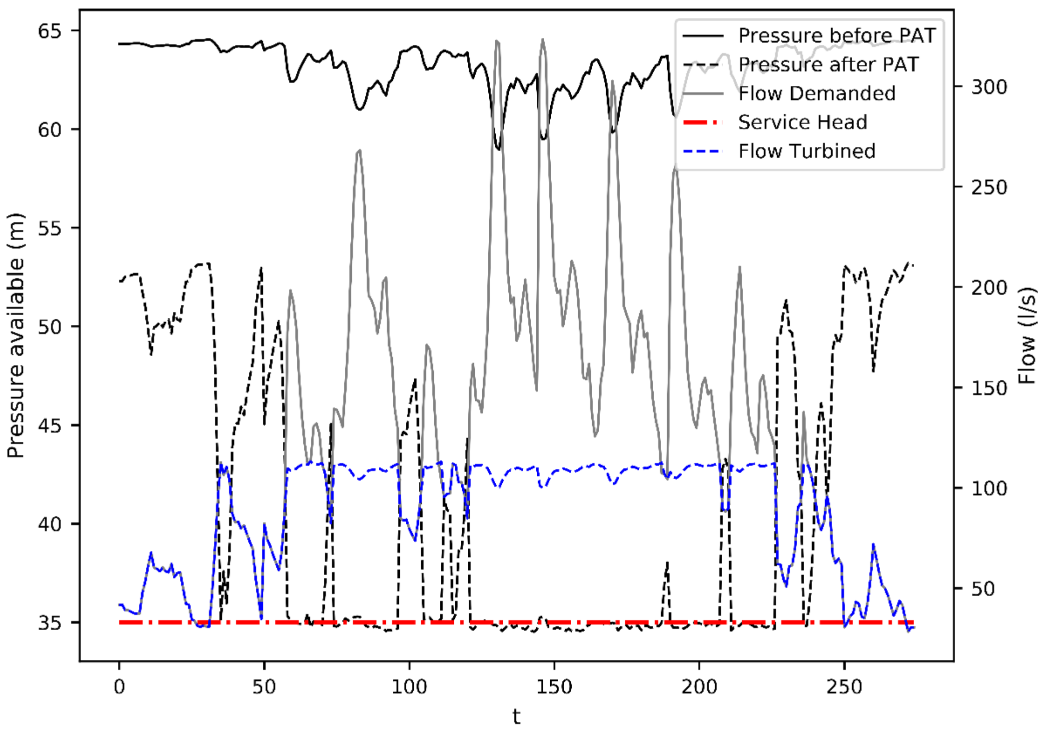

Figure 5-8. *Analysis of the actual pressure available in the EPP7 and its variation when the predicted PAT works.*

5.5. Conclusions

Micro hydropower has been shown as a potential measure to improve the energy efficiency of water networks. In recent years, pump-as-turbines (PATs) have been highlighted for their potential benefits as an application of micro-hydropower (MHP) in water distribution networks. However, PATs come with disadvantages of relatively low peak efficiencies, which can be reduced further with large flow fluctuations. MHP and PATs in particular applied in irrigation networks is a relatively new area of research focus for these devices, and one that poses significant opportunities for energy saving as well as significant challenges due to variations in flow rate. This chapter aimed to validate a methodology for quantifying the existing potential energy recovery in pressurised irrigation networks where no flow or pressure data is recorded.

The overall result of the methodology comparing actual records and predicted data was satisfactory. In the case of the flow, it presented a good fit between the predicted and the actual values, with a MAE and RMSE of 0.0026 and 0.0068 on the occurrence probability. Values for R^2 and efficiency criteria of 0.804 and 0.576 respectively, were obtained. The PAT output variables of the methodology were also analysed, checking how the results varied when applying predicted and actual conditions. The results were very similar, presenting a *MAE* of 1.73 kW and 6.1 MWh, and *RMSE* 0.74 kW and 2.32 MWh for the nominal power and potential energy recovery respectively. The efficiency criteria for these two variables were R^2 of 0.720 and 0.903 and *E* of 0.553 and 0.622 respectively. The use of this methodology in networks with no recording devices installed could help network managers to estimate power and the energy recovery potential. Once quantified, the potential economic and environmental savings could be measured, and the viability of PAT installations deeply studied. An important point to stand out is the results achieved when PATs obtained under both conditions, predicted and actual, were simulated in under actual conditions. The energy recovery predictions were almost identical, with a difference of 0.2% over the whole amount of energy recovery in the network.

Future research will apply this methodology on a much larger set of irrigation networks. Thus, the potential improvements that MHP could cause on energy efficiency in pressurised irrigation networks will be assessed. Potential economic and environmental benefits will be quantified, comparing them with the results obtained in previous research where other energy reducing measures were applied. The application of MHP together with other of these measures will be studied.

6 LARGE-SCALE ASSESSMENT

6.1. Introduction

Previous studies on hydropower energy recovery in water networks were limited to drinking water, assessing the potential from measured flow and pressure data in networks with existing hydraulics models in some cases. These investigations also covered just a small part of the existing infrastructure in those locations. Different studies also assessed the potential of MHP as a measure to improve the energy efficiency in pressurised irrigation networks. Nonetheless, each of them used different approaches to quantify the potential, and different input flow and head data. These encompassed predicted or recorded annual mean values, or predicted or annual recorded values. This fact makes joining all these results in one study to assess the large-scale potential, significantly complex.

As previously mentioned, none of the previous investigations examined this impact beyond a single case study or on a large regional scale. The difficulty in obtaining the detailed water network information required for such investigations is a major barrier to conducting large-scale assessments. Network information on pipe size, layout, water demands and pressure, are often absent, not recorded, or not publicly available. As such, an alternative approach to MHP potential prediction is required using proxy measures of key variables. Mitrovic et al. (2018) analysed the linear correlation between MHP power potential and different proxy variables, such as population, population density and land topography, as predictors of water demand and system overpressure, key variables in MHP potential for drinking water networks.

The 238 sites studied by Gallagher et al. (2015), were analysed by Mitrovic et al. (2018) with a view to predicting large scale energy potential in the absence of network data in Ireland. The results showed a coefficient of determination (R^2) of 0.26 for the population as a proxy measure of MHP potential, and in general failed to offer a reliable prediction of MHP potential for the drinking water sector using this method. Nevertheless, these works were focussed on drinking water and there are not previous investigations for the irrigation sector.

This section of the thesis aims to develop a model to predict the energy recovery potential in pressurised irrigation networks on a large-scale using proxy indicators of irrigation demand and network pressure. Its main novelty falls on being the first attempt at exploring on a large geographical scale, energy recovery prediction in pressurised irrigation networks using hydropower, providing an approximation of the existing resources for such technology. Furthermore, two approaches were assessed: Single linear regression models, as well as non-linear analysis through artificial neural networks (ANNs). These models were evaluated using a database with 177 observations obtained from the detailed hydraulic model of 18 irrigation networks employing data from the 2018 irrigation season. Three different variables were utilised to evaluate their relationship with the energy recovery potential, measuring distinct statistical metrics in each model. ANNs provided the best results and were finally applied to prediction of large-scale the energy recovery potential. The prediction was conducted for every municipality forming the provinces of Seville and Cordoba, in Southern Spain. The potential in more than 160,000 ha of irrigated surface was evaluated, assessing the economic and environmental benefits.

6.2. Methodology

The observations required to develop and test a prediction model were obtained from 18 pressurised on-demand irrigation networks, most of them located within the provinces of Cordoba and Seville, in Southern Spain. Two of the networks were out of this region, one located in Southern Portugal and the other in South Western Spain (see Figure 6-1). The annual energy recovery potential was calculated for these networks for the 2018 irrigation season, using the methodology developed and validated in Chapter 4 and 5. The aforementioned methodology aimed to predict the flow distribution along the irrigation season, assessing every possible flow value predicted as a best efficiency flow for different theoretical hydropower turbines.

The methodology in particular relies on the use of pump-as-turbines (PATs), conventional pumps operated in reverse as turbines, which have been shown to be suited to the micro scale applications present in irrigation networks (Tarrago, 2015; Pérez-Sánchez et al., 2016; Pérez-

Sánchez et al., 2017; Pérez-Sánchez et al., 2018; Garcia-Morillo et al., 2018) and also be to be economically viable in this setting due to their low-cost nature (Novara et al. 2019). The methodology developed in Chapter 4 and validated in Chapter 5 enables the selection of the PAT that returned the minimum payback period from all possible best efficiency flows within the analysed network. It used a simplified variable operating strategy (VOS) (Carravetta et al. 2013b; Fecarotta et al. 2016), which considered the whole flow and head distribution, simulating the theoretical behaviour of the machine for these values.

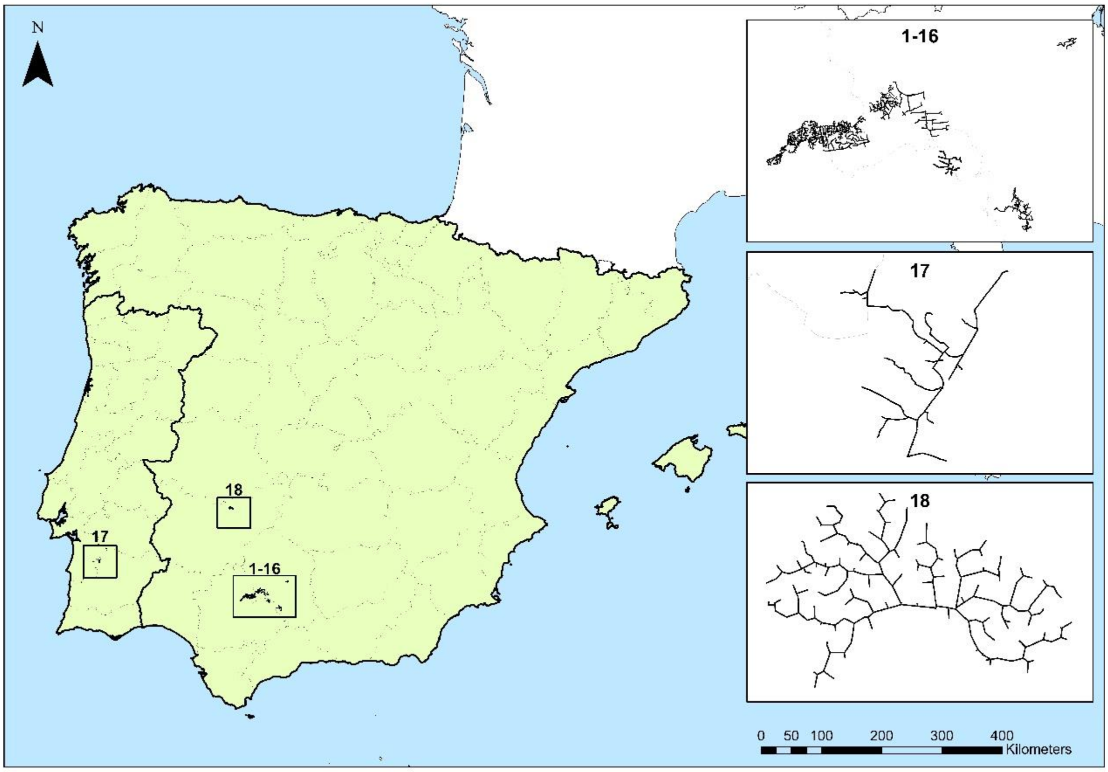

Figure 6-1. *Location and summary of the networks analysed to obtain the observations.*

The 18 networks irrigated a total surface of 36,536 ha, where a wide distribution of crops were cultivated. The infrastructure was either gravity fed or supplied through direct pumping, depending on the network. The service pressure required at hydrant level in every case was 35m. The irrigation networks worked as 18 independent hydraulic infrastructures, corresponding to nine different irrigation districts. Eight of the networks belonged to nine different districts, while the other ten were different sectors within the same district. The different districts analysed were: Genil Margen Izquierda (GMI), Bembézar Margen Izquierda (BMI), Bembézar Margen Derecha

(BMD), El Villar (EV), Genil-Cabra (GC), Guadalmellato (GU), Fuente Palmera (FP), Aboro (AB) and Zújar (ZJ).

A summary of each irrigation district, their crops and characteristics, can be seen in Table 6-1. In addition, all the networks analysed were fed by surface water coming from different infrastructures (rivers or irrigation channels), from which the water was pumped either to a reservoir, if the network was gravity fed, or directly pumped into the network. The networks were designed for a high demand, 1-1.2 l s^{-1} ha^{-1} on demand (24 hours per day) and simultaneity of 100%, which means that all the hydrants could be open at the same time. Lastly, the dominant irrigation system in all the networks was drip irrigation.

Table 6-1. Summary of the main properties of the irrigation districts assessed.

District	Networks Analysed	Irrigated Surface (ha)	Dominant Crops	Feeding system	Country
Genil Margen Izquierda	1	4450	Citrus, Almond, Olive, Walnuts	Gravity	Spain
Bembézar Margen Izquierda	1	3900	Citrus, Maize, Olive, Sunflower	Pumping	Spain
Bembézar Margen Derecha	10	11,163	Citrus, Maize, Cotton, Sunflower	Pumping	Spain
El Villar	1	2726	Cereals, Cotton	Pumping	Spain
Genil-Cabra	1	4320	Cotton, Sunflower, Wheat	Pumping	Spain
Guadalmellato	1	475	Maize, Cotton, Sunflower, Wheat	Pumping	Spain
Fuente Palmera	1	5611	Cotton, Sunflower, Wheat	Pumping	Spain
Aboro	1	1200	Olive, Maize, Almond	Gravity	Portugal
Zujar	1	2691	Tomatoes, Maize, Vine, Fruit, Rice	Pumping	Spain

6.2.1. Potential MHP locations

Applying the methodology developed and validated in Chapter 4 and Chapter 5 respectively, to the 18 irrigation networks resulted in the identification of 177 specific locations where the installation of a PAT was economically viable. The irrigated surface encompassed by the 177 potential points for micro-hydropower energy recovery was 27,417 ha, accounting for an energy recovery potential of 6.11 GWh. Table 6-2 shows a summary of the results obtained for each independent irrigation network, showing among others the number of viable points for MHP application, total energy potential or percentage of surface where potential was found.

Table 6-2. *Results summary obtained for the 18 irrigation networks.*

Network	Points	Energy (MWh)	Surface (ha)	Surface with MHP potential	Average Power (kW)	Average Energy (MWh)
GMI	17	662	4450	62.0%	15.4	39.0
BMI	15	744	3900	88.7%	24.5	49.6
BMD-S3	4	46	631	56.8%	2.9	11.4
BMD-S4	8	98	1679	48.6%	5.5	12.3
BMD-S5	3	59	1186	47.8%	8.4	19.5
BMD-S6.1	15	452	726	92.9%	17.1	30.1
BMD-S6.2	3	107	924	92.5%	11.3	35.5
BMD-S7	5	94	922	66.3%	5.0	18.8
BMD-S8.1	4	123	1141	70.1%	9.9	30.8
BMD-S8.2	8	127	1686	53.7%	15.8	15.8
BMD-S9	5	132	1275	83.0%	7.1	26.5
BMD-S10	3	80	993	70.2%	8.9	26.7
EV	13	917	2726	94.3%	28.8	70.5
GC	34	1165	4320	88.4%	24.9	34.3
GU	1	16	475	21.1%	6.5	16.3
FP	26	934	5611	91.0%	20.0	35.9
AB	4	79	1200	74.6%	6.4	19.7
ZJ	9	281	2691	58.2%	8.1	31.2
Total/Average	**177**	**6114**	**36,536**	**70%**	**16.9**	**34.6**

Relating the irrigated surface, where energy recovery potential was found, with the total irrigated surface analysed in the 18 networks, resulted in a ratio of 0.75. However, looking individually to each network analysed, the average value of this factor decreased to 0.70. This factor showed the portion of irrigated surface where MHP potential was found with a payback period less than 10 years. The mean power found per observation was 12.6 kW, with minimum and maximum power of 1.6 kW and 62.3 kW respectively. With respect to energy, the average amount found per location was 29.1 MWh, with minimum and maximum values of 3.8 MWh and 214.7 MWh respectively.

These 177 potential MHP installations were used as the basis for the assessment of the large-scale prediction methodology described in the following sections. Using linear and non-linear techniques, proxy variables were used to attempt to predict this potential energy production in the absence of specific measured irrigation network data on flow, pressure, pipe layout, pipe diameter, etc.

6.2.2. Proxy Variables Definition

Like in any prediction model, the definition of one or several explanatory variables, determined as inputs, was required to predict the output or response variable. To allow the application of this model to regions with pressurised irrigation networks, the explanatory variables were chosen considering the possibility of easily gathering these independently of the area studied. The output variable used was the MHP energy recovery potential. The explanatory variables selected in this model were selected to characterise different aspects of the area where the potential was analysed. Therefore, these variables were: the irrigated surface area; theoretical irrigation requirements; and mean slope.

The irrigated surface area, in hectares, was the first variable considered, since the larger surface, the higher the probability to find MHP potential. Irrigated surface area was a proxy measure of pipe flow rate as large surface areas will require greater flows and therefore could have a higher potential for hydropower production.

The irrigation requirements, in m^3 $year^{-1}$, depended on the crops cultivated and on the agro-climatic parameters (rainfall and evapotranspiration) of the area studied. Crops with higher irrigation requirements would lead to a greater irrigation time, which would again affect flow rates and potential energy production in a turbine. On the other hand, in areas with high rainfall and low evapotranspiration, the irrigation requirements would be lower and so the irrigation time and vice versa. Therefore, this variable also considered climatic conditions as a proxy.

Finally, the mean slope in percentage was introduced in the model to represent how the terrains topography affected the energy recovery potential. It was assumed that the mean ground slope would be related to potential overpressure within the network and areas with higher slopes were more likely to contain overpressures. In this way, the model was applied in each area analysed, once the proxy variables were gathered, identifying more or less potential depending on the distribution of these variables in each specific site.

Downstream of the 177 potential MHP locations found in each network, the irrigated surface was considered as a unique plot, independent of the number of hydrants found. Therefore, the irrigated surface, defined as one of the explanatory variables, was obtained. To calculate theoretical irrigation requirements for every location, the crop distribution as well as the agro-climatic parameters (rainfall and evapotranspiration) were required. The crop distribution was known for every location from the development of the 18 hydraulic models. Regarding the agro-climatic parameters, the information was gathered from the closest weather stations in each case. The theoretical irrigation requirements were then calculated applying the method proposed by Allen (1998) using the CROPWAT software (Smith 1992). The mean slope in percentage was calculated for each point considering the distance and the height difference between the water source and the most critical hydrant for each location. This was the hydrant with the lowest head available of the branch assessed, when 100% of the hydrants were open simultaneously.

6.2.3. Linear analysis

The first stage of the study was conducted assuming the relationship among the variables was linear, which reduced the complexity of the problem. Thus, single linear analysis was first carried. The input variables were related one on one to the response variable. The correlation coefficient (r), coefficient of determination (R^2), the mean squared error and the mean absolute error (MAE) were used as statistical metrics to evaluate the existing relationship. High values of the coefficient of determination would indicate linearity, against low values, which would indicate no linearity in their relationship. The entire sample of 177 locations was used to do this analysis. The different linear models evaluated followed Equation (6.1), where a is the y-intercept vector, b is the slope vector and x_i referred to the different input variables used.

$$Y(x_i) = a + bx_i \tag{6.1}$$

6.2.4. Non-linear analysis

In order to consider non-linearity among the variables selected, ANNs were used for this analysis. ANNs are structures or models used for the learning process carried out in machine and deep learning approaches, structured in layers stacked on top of each other (Chollet 2018). The general structure of these models is composed by an input layer, which corresponds to the explanatory variables, hidden layers, used to transform the inputs into outputs, and an output layer, which is the expected value. Each of these layers has a number of neurons, which should be defined specifically for each problem. Multilayer neural network general scheme is shown in Figure 6-2.

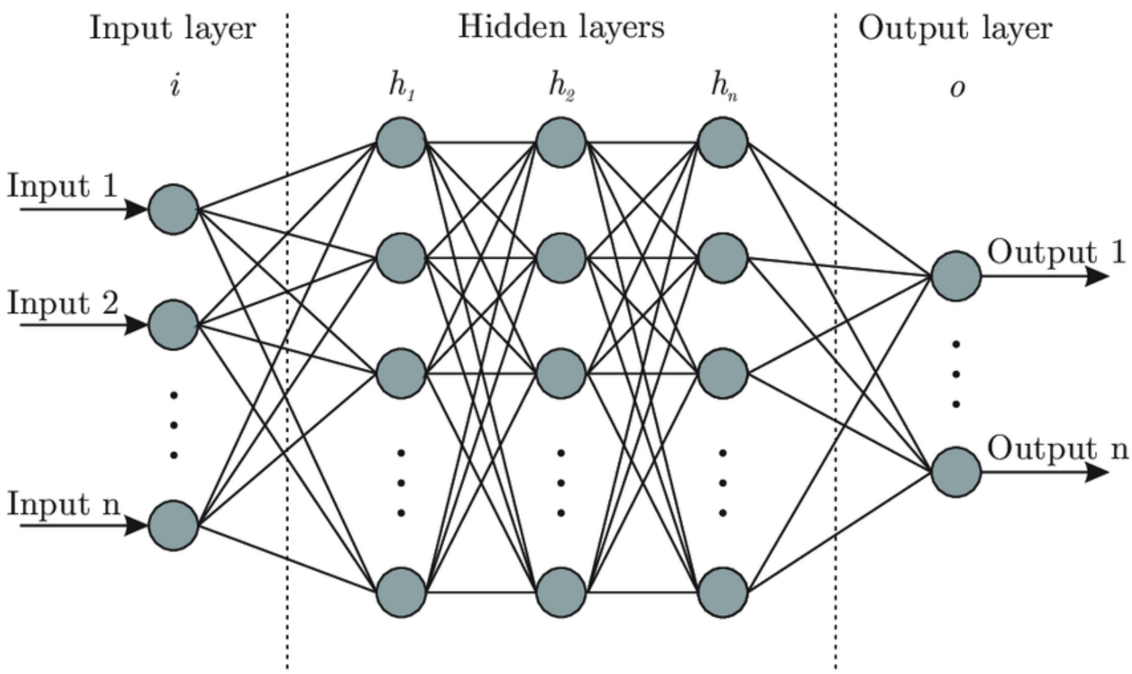

Figure 6-2. *Multilayer ANN general scheme*

ANNs are able to predict an output using different input variables, and are capable of adapting to non-linear relationship between output and input. ANNs have been applied in several engineering fields, such as rainfall forecasting, time variables prediction or water demand forecasting in irrigation networks (Abrahart and See 2000; French et al. 1992; Gutiérrez Estrada et al. 2015; Kuligowski and Barros 2002; Park 1998; Perea et al. 2015; Pulido-Calvo et al. 2007, 2003; Pulido-Calvo and Gutiérrez-Estrada 2009; Pulido-Calvo and Portela 2007; Pulido et al. 2002; Zhang et al. 1997).

A first barrier was found when ANN was used as the forecasting method: the small sample set. Although some literature advises that big data sets are required to use deep learning techniques in order to avoid overfitting and have a good performance, it was also found that the samples should be greater than 100 (Github, 2017). In this case, 177 observations were taken into account when the model was created, fulfilling this requirement. Moreover, the overfitting was analysed when the ANN was being defined, as it can be latterly seen in Figure 6-5.

In addition, ANNs are considered as a powerful tool for forecasting. Despite their complexity, more accurate results could be obtained using them rather than other prediction methods. Furthermore, ANNs have been used in several research studies for predicting different variables related to irrigation, as aforementioned. Thus, the use ANNs would spread their application in the irrigation field. Another key aspect considered was the ability of ANNs to fit to non-linear problems, modelling those returning feasible results.

6.2.4.1. Data Transformation

As the different input variables had different units, this fact could lead to some difficulties during the ANN learning process, since the range of values for each input variable could be widely different. There are several methods to avoid such problems while improving the accuracy of the model, such as normalisation or transformation. Different variable transformations were tested. In this case, logarithmic transformation was selected just for the irrigation requirements, since the range of values found for this variable was normally much higher than the other two variables and the results obtained were significantly better than with other transformations. Using this transformation, the values were brought into a more similar value range to the other explanatory variables, following Equation (6.2).

$$X' = \log(X) \tag{6.2}$$

Where $X'$is the value transformed, X is the actual input data.

6.2.4.2. ANN Network structure

During the model definition, we have to set, among others, the number of neurons on each layer, the number of hidden layers and the number of epochs. In addition, inputs and outputs were previously defined. The number of hidden layers tested varied between one and two, in which different numbers of neurons were tried, varying between 2 and 64. The sample was divided into a training and validation set. Different size distributions of these sets were tested, analysing the minimum squared error (MSE) for each distribution in each fold, which refers to the number of random groups that a given data sample is to be split into, and selecting the one returning the minimum mean value. Four different folds were randomly selected, optimising the objective function for each number of hidden layers, neurons and sample distribution in every fold. Since the size of the sample was small, the scores obtained for each fold could vary from one fold to another. Thus, average results for the four folds were considered in order to obtain more accurate results. The minimum average of the four folds was calculated, whose structure was fixed as the optimal. The number of epochs tried oscillated between 1 and 300 for each possible configuration.

The gradient descent optimisation algorithm ADAM (Adaptive Moment Estimation) (Kingma and Ba 2014) was implemented in Python for the learning process, aiming to obtain an optimal prediction of the energy recovery existing potential. The adaptive moment estimation algorithm (Kingma and Ba 2014) is a first-order gradient-based optimization of stochastic objective functions. It was defined by its developers as a straightforward method to implement, that requires little memory and is computationally efficient. The ADAM method combines the main advantages of two methods: AdaGrad (Duchi et al. 2010) and the RMSProp (Tieleman and Hinton 2012), two other gradient-based methods. The method was tested in three different types of deep learning problems (logistic regression, multilayer ANNs and convolutional ANNs), returning better outputs that other gradient-based methods (see Figure 6-3 for multilayer ANNs comparison). ADAM returned a better convergence than the other methods.

The objective function was used to measure the performance on the training and validation data. The MSE was used as the objective function (Equation 6.3), which measured the average of the square of the errors. The optimal configuration was provided by the structure whose MSE was the minimum. The relationship between the input and output in a neuron was analysed using an activation function. To consider non-linearity, the Rectified Linear Unit function (ReLU) was used, since it was more computationally efficient than other non-linear functions, such as the sigmoid (normally used for binary classification problems), hyperbolic tangent (used for zero-concentrated problems) or softmax (used for multilabel classification problems). Mathematically, this function is expressed as per the Equation (6.4).

$$MSE = \frac{1}{N}\sum(y_i - \hat{y}_i)^2 \tag{6.3}$$

$$f(x) = \max(0, x) \tag{6.4}$$

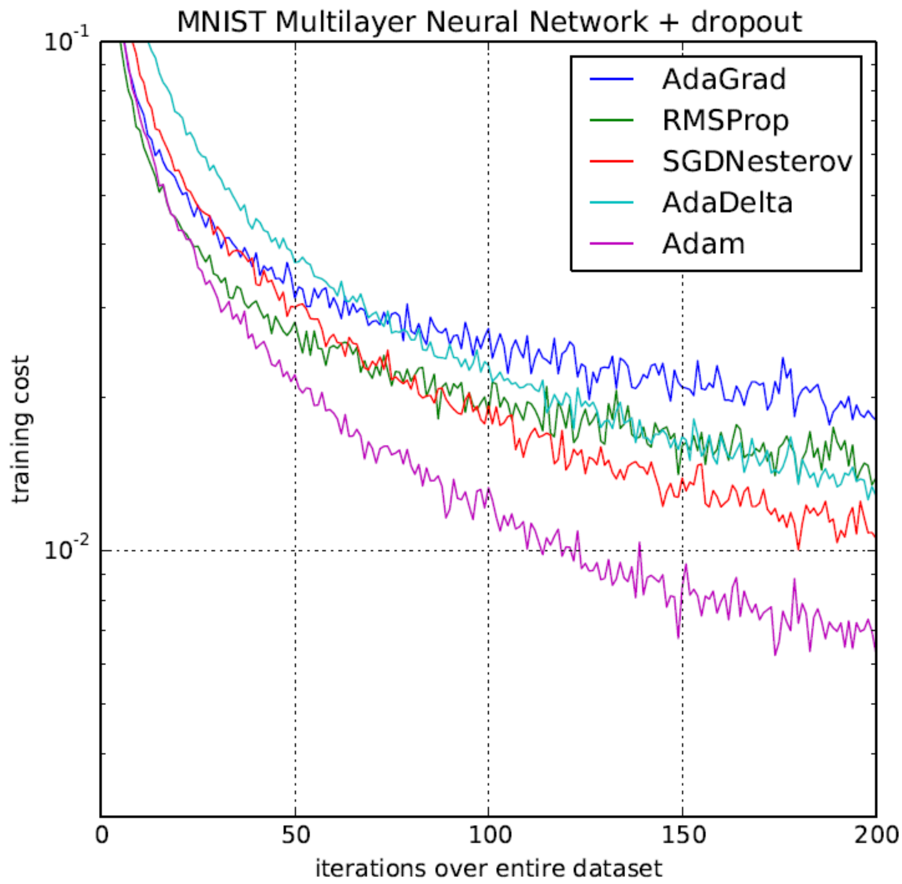

Figure 6-3. *Comparison between Adam algorithm and other stochastic first order methods applied in multilayer ANNs* (Kingma and Ba 2014).

6.2.5. K-fold cross validation

The validation of the ANN model was carried out running k-fold cross validation, consisting of the partition of the whole sample into *k* equal sets randomly selected (see Figure 6.4). For this purpose, the observations were split into training and validation sets, corresponding to the distribution, which returned the best results during the network architecture definition. For each fold, the input data corresponded to the training data of the explanatory variables and the output to the energy recovery potential of the same set. Using the validation data, the output variable was predicted inputting the data corresponding to the explanatory variables of the same set. Comparing the predicted values with the observed ones, two statistical metrics were calculated: the mean absolute error, expressed in the same units to the output variable; and the coefficient of determination, whose value varies within the range [0-1].

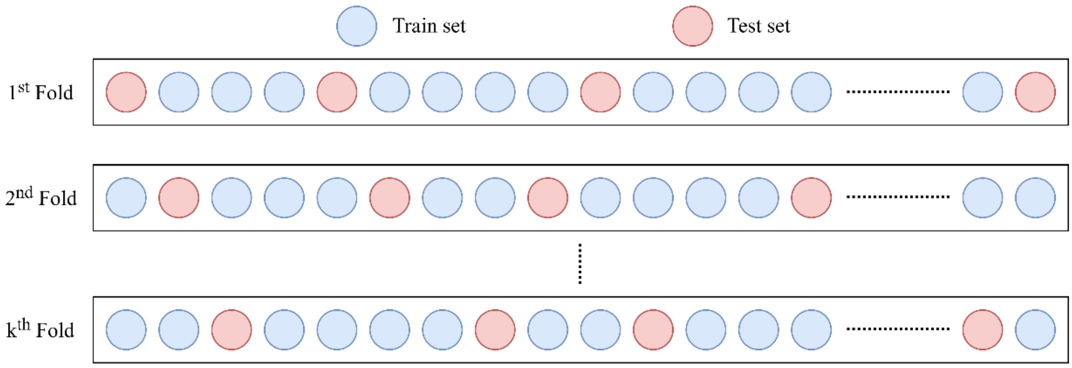

Figure 6-4. *General scheme of the K-fold validation method*

6.2.6. Application to large geographical scale predictions

Finally, the models were compared, selecting the one that provided the best metrics. This was used to predict the energy recovery potential in every municipality in the whole province of Seville and the province of Cordoba. The potential of 180 municipalities was predicted, 105 of them corresponded to Seville and 75 to Cordoba. The input variables were gathered for these municipalities from the SIGPAC platform (Junta de Andalucia 2019), where different information, such as crop cultivated, mean slope or irrigation coefficient were found for all the plots of each municipality. A database with around 20 million data points was compiled and analysed for the whole region. Thus, the surfaces with crop cultivations were extracted, calculating the theoretical irrigation requirements for all of them. The agro-climatic parameters were obtained from 29 weather stations distributed around Seville and Cordoba. For the mean slope of each municipality, a weighted measure was calculated, considering the mean slope for each plot containing crops, as per Equation (6.5). The irrigated surface found in every municipality was corrected with the average relation factor aforementioned, which showed the ratio of surface area with viable energy recovery potential found for the networks analysed individually (0.70). This correction was necessary, since otherwise the whole irrigated surface found for each municipality would have potential, which is unrealistic. The dominant crops found were olive trees and citrus, which occupied 66.7% and 23.4% of the total irrigated surface respectively.

$$S_m = \frac{A_1}{A_T} S_1 + \frac{A_2}{A_T} S_2 + \cdots + \frac{A_n}{A_T} S_n \tag{6.5}$$

Where S_m is the mean slope for each municipality; $A_{1,}$ $A_{2,}$ A_n correspond to the area of the plots 1,2 and n respectively, where crops were found; A_T is the total irrigated area with crops; and $S_{1,}$ $S_{2,}$ S_n were the mean slope for the plots 1, 2 and n.

6.2.7. Environmental, energetic and economic analysis

To assess the potential benefits associated with the adoption of MHP technology, two analyses were carried out for the outputs predicted for Seville and Cordoba. The environmental quantification of these benefits were measured calculating the potential emission savings in t eCO_2, using the energy predicted for both provinces, and the national emission factor of Spain for 2018, 0.246 t eCO_2 MWh^{-1} (Red Eléctrica de España 2019b). For the energy analysis, a general comparison between the energy consumption and the potential recovery was conducted. Rodríguez Díaz et al. (2011) estimated an average energy consumption per unit of irrigated area of 1,003 kW ha^{-1} for ten pressurised irrigation districts located in Southern Spain, which contained 11 of the networks used in this research, all of them located in Andalusia. Regarding the economic analysis, the potential savings for the energy cost per irrigated surface unit was calculated. Fernández García et al. (2014b) studied how the energy cost, related to the total water cost, per unit of irrigated area, changed after the modernisation process. Its value was reported for five pressurised irrigation districts, including some of the networks analysed in this research. This value for pressurised infrastructure varied between €48.9 ha^{-1} and €147.6 ha^{-1}. A mean weighted value of €127.5 ha^{-1} was used.

6.3. Results

6.3.1. Linear Analysis

The results of simple linear regression approach varied widely depending on the variable considered. The highest r and R^2 were obtained for the irrigated surface area (0.754 and 0.569 respectively) whilst the lowest was obtained for the slope (0.0071 and 0.005). Nevertheless, it could be seen that the relationship between the irrigated surface area and the energy potential was not strongly linear. Concerning the MSE and MAE, the model using the irrigated surface area as an input returned the best results for both metrics, with 479.67 MWh and 15.27 MWh respectively. The outcomes of this analysis were shown in Table 6-3. The graphical results of the fitting can be seen in Figure 6-5.

Table 6-3. *Linear analysis results for single models.*

Single	a	b	**r**	**R^2**	**MSE**	**MAE**
Irrigated Surface	9.691	0.157	0.754	0.569	479.67	15.27
Irrigation Requirement	-249.464	48.95	0.609	0.37	700.36	18.85
Slope	36.754	-2.749	0.071	0.005	1106.92	22.69

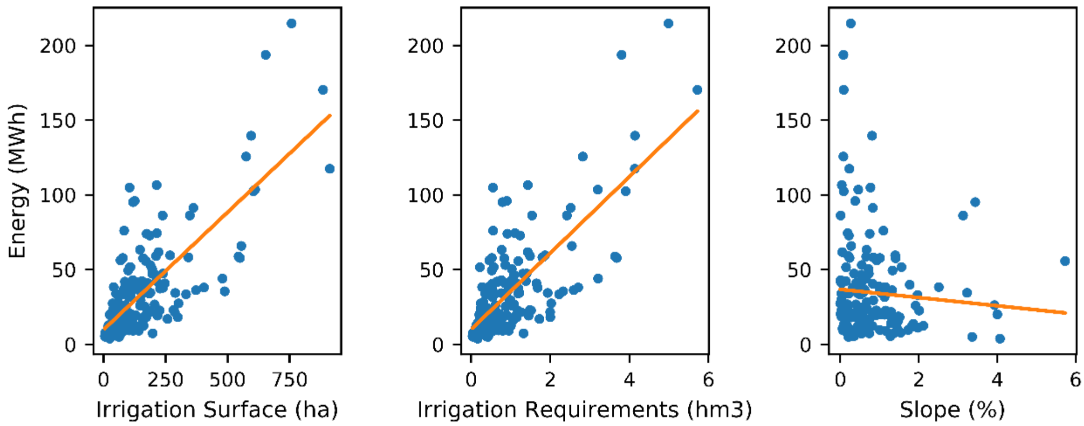

Figure 6-5. *Linear regression trendlines for the three proxy variables*

6.3.2. Non-linear analysis

The different results from the non-linear analysis carried out to define the ANN network structure can be seen in Figure 6-6, where each line represented a different number of neuron configurations. The average MSE for the four folds is represented for each configuration for every number of epochs run for two hidden layers. The observation distributions among training and validation sets that provided the best results yielded 74%-26% respectively. In order to evaluate how this distribution could affect the model performance, the mean and standard deviation was calculated for each fold, obtaining slight differences between the training and validation sets. More specifically, the maximum differences were obtained in fold 2 for the mean value (17.6%) and in fold 4 for the standard deviation (17%). Therefore, the training data set included 130 observations and the validation set included 47. Two hidden layers composed the structure with the minimum MSE, with 26 and 18 neurons respectively. The minimum MSE obtained by the aforementioned structure can be seen and compared with the rest of the structures tested in the zoom plot of Figure 6-6.

Concerning the overfitting, all of the lines tended to increase their slope after reaching a certain number of epochs, so a greater number of epochs for those would be translated in an overfitting on the model. The minimum MSE was achieved by the previously defined structure after running 36 epochs, with an average value of 383.3 MWh for the four folds.

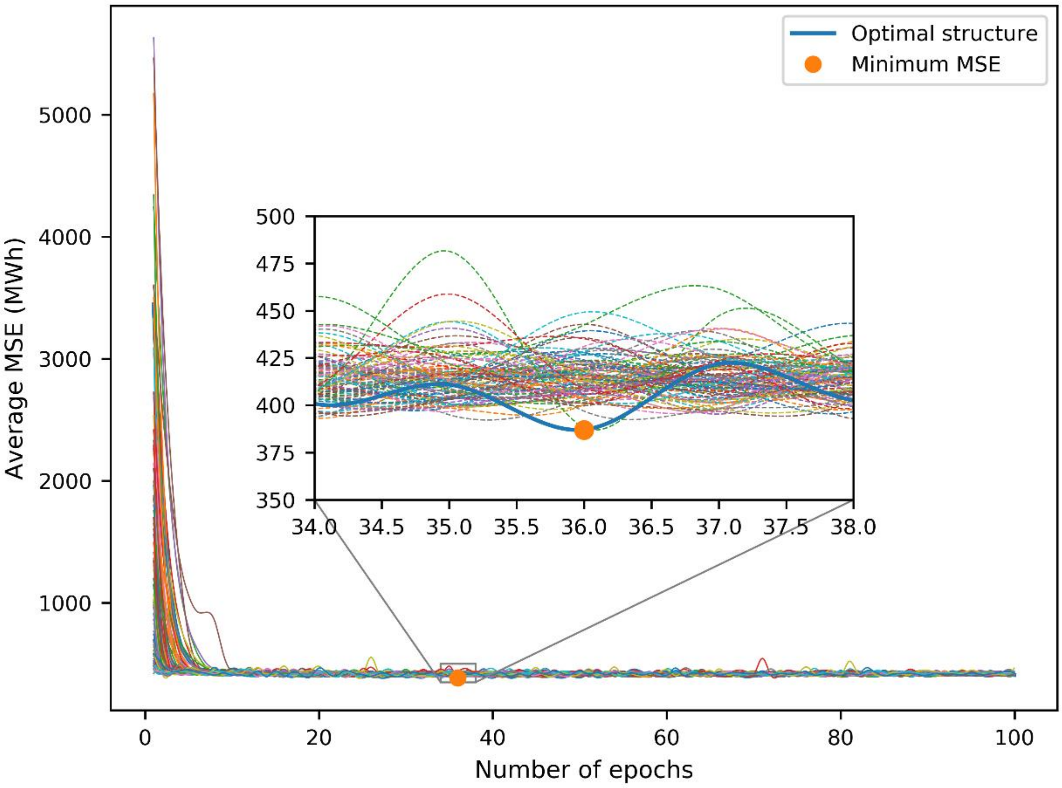

Figure 6-6. *Average MSE of the four folds for each configuration of neurons in each epoch.*

Once the structure of network was defined, the validation was carried out. The results of MSE, which was the objective function, was obtained for each epoch and fold run. The metrics R^2 and MAE were also calculated for every fold. The predicted values compared to the validation ones can be graphically seen in the Figure 6-7. The results showed how the R^2 changed as per the training and validation data. The best approach was obtained using the sets configured in the third fold, with an R^2 of 0.736. The fourth fold prediction was the weakest with R^2 equal to 0.462. The average R^2 obtained from the four folds was 0.631. On the other hand, the MAE of the different folds varied between 13.25 MWh and 15.59 MWh, with an average value of 14.52 MWh. This average obtained from the four folds MAE was used to correct the predicted values of each the municipality in Seville and Cordoba, since it represented a more reliable metric than using the

MAE obtained from a unique fold. The correction was carried out considering both, positive and negative MAE, thus adding or subtracting it to the value predicted.

Comparing the test and predicted values for the folds considered and analysing the errors aforementioned, it was found that the sum of energy of the test set was lower than the predicted for the first fold and greater for the three remaining. The difference found between the total amount of energy for both, test and predicted sets, varied between 5% and 18%. Although the MAE showed high relative errors for single observations (44% in the worst case), when the whole set was compared, these errors significantly decreased. Furthermore, when the total average energy value, for test and predicted sets, of the four folds were compared, the difference found was just 6.5%, which could be considered acceptable for prediction purposes. This overall error was also used to correct the potential forecasted in the municipalities.

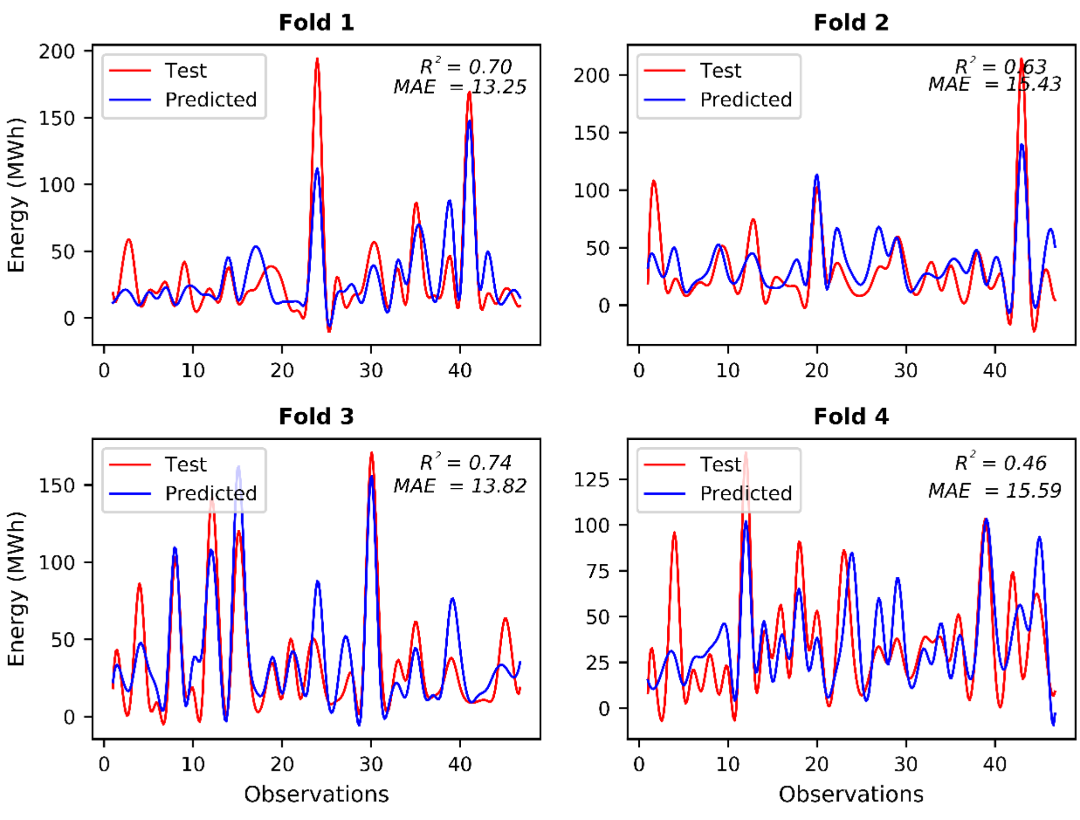

Figure 6-7. *Comparison between test observations and predicted values for each fold.*

The objective function (MSE) got its minimum in the third fold (320.90 MWh), with an average value of 383.3 MWh. The difference between the results obtained for first three folds and the fourth one could come from different distribution of MHP locations on the training set used. The distribution of MHP turbine energy around the mean value is uniform in the first three folds (see Figure 6-8), with a percentage of observations below and over the mean value of 62.3% - 37.7%, 61.5% - 38.5% and 63.8% - 36.2% respectively. Although for the fourth fold this percentage is similar to the other folds (64.6% - 35.4%), analysing the standard deviation (in MWh), it could be deduced where this difference in the coefficient of determination is coming from. The values obtained for the first three folds were 32.4, 32.8 and 32.4, while for the last one it was 34.8. This fact showed a wider distribution of the training set points of the fourth fold from its mean value.

On the other hand, when the validation sets were analysed the results showed opposite trends than in the training sets. Thus, the standard deviation of the first three folds was 35.6, 34.4 and 35.8 respectively, while for the fourth it was 28.9. A summary for each fold for the different results is shown in Table 6-4, as well as the mean and standard deviation values for the train and test sets.

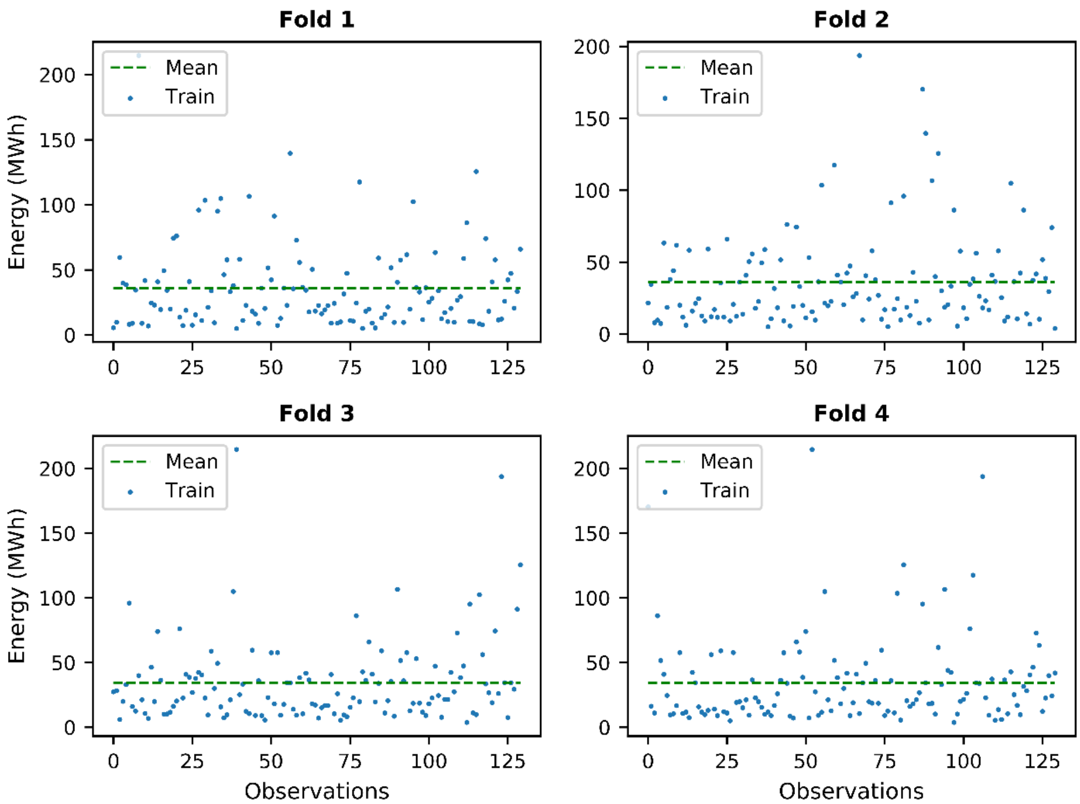

Figure 6-8. *Training set distributions from the mean value for each fold.*

Comparing the results obtained using ANNs with the linear analysis, it can be seen how the MSE values are significantly lower. The MSE achieved in the third fold was around 36% lower than the MSE accomplished in the multivariate linear analysis using all the variables. This difference kept increasing when the number of variables decreased. The four folds average minimum MSE achieved in this last model was 20.5% lower than the MSE obtained in the three variables linear multivariate analysis.

When other metrics were compared, ANN also showed better results. The maximum R^2 attained in the third fold was almost 30% greater than the best value achieved in the linear analysis. When the average result was equated, the results improved by 10%. However, a 10% improvement could be considered large in this case, as the sample was split into two sets for the ANN model but used in its entirety for the linear analysis. Finally, the MAE obtained in the first fold was 13.5% smaller than the best result obtained in the linear analysis, decreasing this difference down to 5% when the average MAE was compared.

Table 6-4. *Mean values and standard deviations obtained for each fold for the train and test sets.*

K	***R^2***	***MAE***	***MSE***	**Mean**		**Standard Deviation**	
				Train	Test	Train	Test
1st Fold	0.698	13.25	369.8	35.9	30.8	32.4	35.6
2nd Fold	0.627	15.43	396.8	36.3	29.9	32.8	34.4
3rd Fold	0.736	13.82	320.9	34.5	34.7	32.4	35.8
4th Fold	0.462	15.59	445.8	34.5	34.8	34.8	28.9
Average	0.631	14.52	383.3	-	-	-	-

6.3.3. Prediction in municipalities

With the network already defined and validated, the energy recovery potential for every municipality of the provinces of Seville and Cordoba was predicted. The pressurised irrigated surface raised up to 163,472 ha, comprising around 6% of the total surfaced encompassed in both provinces, from which 114,430 ha were analysed, obtained after applying the correction factor outlined in the Materials and Methods Section (0.7).

The total energy potential predicted for the whole region varied between 19.64 and 22.38 GWh, depending on the fold used. The average potential predicted was 21.05 GWh for 2018. Applying corrections for the previous errors observed between test and predicted sets for the four folds, 6.5%, the energy varied between 19.7 and 22.4 MWh. Applying the average MAE from the folds analysis, 14.52 MWh to the average value obtained for each municipality as correction measure, a minimum and maximum energy of 18.95 GWh and 23.70 GWh were obtained. This value was distributed among the 180 municipalities, among which, six were found not to have irrigated surface or energy recovery potential (see Figure 6). It can be observed how the different values obtained after applying different correction measures were similar, with differences oscillating between 6.5% and 12.5%. An average value of 114.4 MWh per municipality was found.

The greatest potential was predicted to be found in Ecija (Seville), with an annual value of 1.63 GWh. If the variables were analysed, it seems rational that the maximum potential was found there, since more than 9,000 ha were found to be irrigated, whilst the average irrigated surface per municipality was 636 ha. Its average slope was 7.8%, whilst the average slope of the municipalities was 5.5% However, most of the municipalities showed a potential lower than the average, accounting for around 71.7%, with a potential lower than 100 MWh per year. More than 50% of the potential predicted was concentrated in 20 of the sites analysed, which irrigated around 60% of the surface considered. Evaluating the case of Ecija and inputting a slope of zero, the energy potential estimated increases in every fold, giving an average value of 1.82GWh per year. Therefore, it could be extracted that high slope values return lower values of predicted energy recovery. The map showing the predicted potential is presented in Figure 6-9.

6.3.4. Energetic and economic analysis

Considering the energy consumed in the entire irrigated surface found in Seville and Cordoba, the percentage of energy that could have been saved in 2018 in the irrigation sector was 12.8%. Introducing this percentage of energy savings into the energy cost index per unit of irrigated surface area, it was estimated that this index could be reduced from €127.5 ha^{-1} to €111.1 ha^{-1} using the average value given by Fernández García et al. (2014b).

Accounting for the average energy potential predicted and using the emission factor for Spain during 2018, the greenhouse gases emissions that could have been saved for 2018 increased to over 5,000 t eCO_2. These results showed the potential environmental benefits that could be achieved if all of this energy was introduced into the grid or consumed on site.

However, it would be optimistic to suggest that all of this energy potential could be directly introduced to the grid or used at the point of production as self-consumption. In the irrigation sector located in agricultural and often rural areas, the likelihood of lack of grid connections or local energy demands close to points where MHP turbines could be installed is moderate.

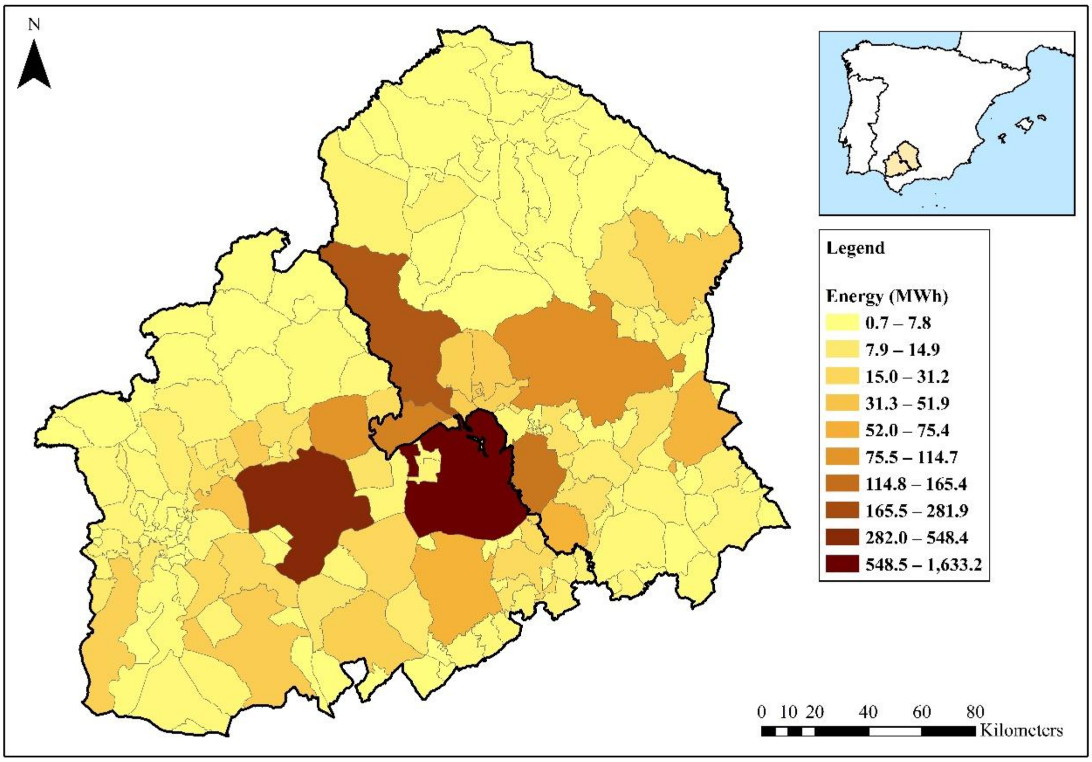

Figure 6-9. *Energy recovery potential found for every municipality of Seville and Cordoba during the year 2018.*

6.4. Discussion

Sustainability requires, among others factors, enhancement of the use of non-fossil fuel energy sources. The existing water networks present, in many cases, an overpressure that is being dissipated in different ways. Micro hydropower (MHP) appears as a potential solution for renewable energy to be implemented in different fields within the water industry, transforming part of the potential energy, represented in the form of overpressure in pipelines, into electricity. Previous research for assessing MHP potential were focused in the analysis of those locations where detailed network information was gathered. However, the lack of larger scale assessment in the different sectors encompassed within this industry makes having a clear idea of the existing potential and its benefits more difficult.

The analysis of the energy recovery potential in the 18 networks returned 177 points showing excess pressure. However, the distribution of the number of points found in each network did not follow any statistical trend, but changed in each district due to different causes. An abrupt orography, presenting important elevation differences among the hydrants of a network, large areas irrigated or the undersize of certain parts of the network appeared as the main reasons for this excess pressure to appear. Although most of the networks presenting important energy recovery potential were due to the large irrigated surface or large elevation differences between hydrants (80m – 100m), a few critical points were identified in others.

For instance, Genil-Cabra irrigation network, with an irrigated surface of 4,320 ha and an elevation difference of 80m between the lowest and the highest hydrant, showed the greatest energy recovery potential with more than 1GWh per year. In this case, the most critical hydrant was located at 242 m.O.D. (meters above the Ordenance Datum) and relatively near the pumping station, around 1.8 km far. Thus, the pressure requirements of nodes located at higher elevations influenced on the existing pressure of the entire network under the current exploitation way. One potential solution to decrease the pressure requirements at these nodes would be the installation of booster pumps. This may reduce the overall energy consumption at the network, and hence the MHP potential. Nonetheless, as the orography found was very steep and the irrigated area quite large, the network would still present energy recovery potential at some nodes of the network. Therefore, a combination of potential solutions (critical point detection + MHP) could be applied, which might lead to a significant reduction of the energy consumption. In the case of El Villar irrigation network, a critical node was found. The elevation difference in this network was not as significant as in Genil-Cabra. However, important headlosses were found in the pipe feeding the most critical hydrant, presenting a unit headloss of 51 m km^{-1}, and accounting a total headloss of 55 m. The rate was dramatically improved (7 m km^{-1}) by changing the pipe diameter from 200mm to 300mm. This would decrease the MHP potential, but there would be still some excess pressure due to elevation changes. Therefore, combining the replacement of some pipes and MHP could importantly decrease the annual energy consumption of the irrigation district.

Although other networks irrigated large areas, presented a less pronounced orography, which reduced the MHP potential. Al

An analysis for Andalusia's historical electricity consumption, GHG emissions and renewable energy generation was made from 2013 to 2018 (see Figure 6-10). The Spanish emission factors for the different years were used to quantify the emissions of Andalusia (Red Eléctrica de España 2019b). The energy consumption tended to decrease related to 2013 levels, however from 2014 onwards, it kept increasing by around 1 TWh per year until 2017. The 2018 levels kept constant when compared to 2017. Nevertheless, the GHG emissions, measured in Mt eCO_2 did not follow the same trend as the consumption. They were more related to the ratio of renewable energy generation. When this ratio decreased, it could be seen how the emissions for that year increased and vice versa. Thus, both parameters had a variable trend along those years. Considering that irrigation is the main economic and energy consuming activity in Andalusia and that more activities are included within the water industry, MHP could make an important contribution for the renewable energy sector and the sustainability of irrigation activities.

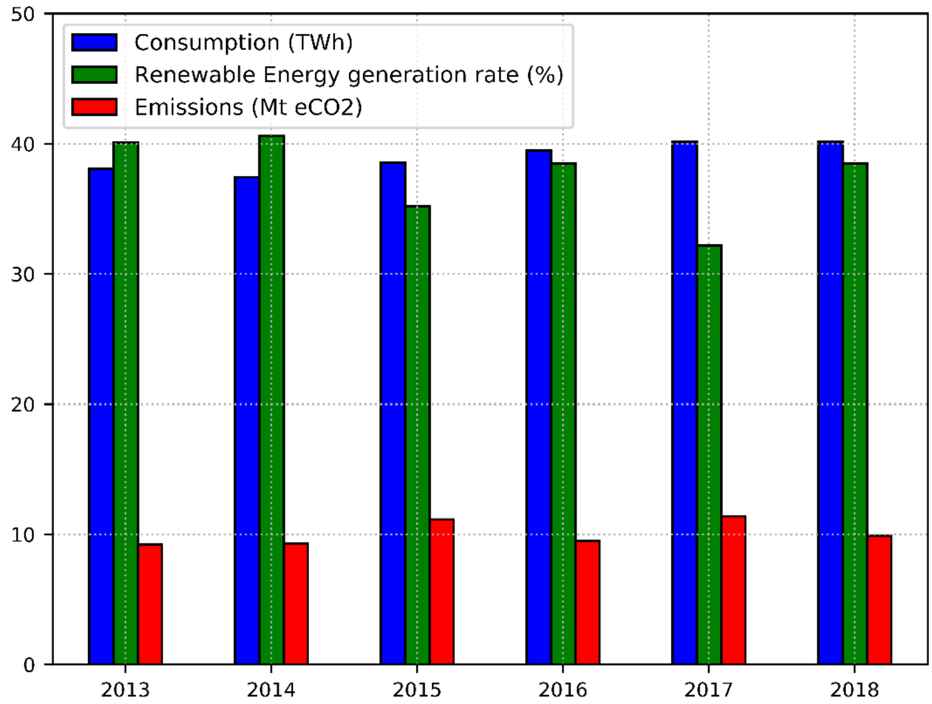

Figure 6-10. *Historical levels of electricity consumption, renewable energy generation rate and emissions for Andalusia.*

The estimated energy savings here would affect the operational cost of irrigation networks, which suffered an increase of 500% after replacing traditional open channels with pressurised networks in Andalusia (Rodríguez-Díaz et al. 2008). Going further, Andalusia accounts for more than a million ha of irrigated surface, of which 84% is pressurised (Ministerio de Agricultura y Pesca 2018). However, the prediction here was carried out just for 15% of this pressurised irrigated surface. The method proposed in this research was employed in regions with similar irrigation infrastructures and design parameters for networks. All of them were design for 100%

simultaneity and a high design demand, which ranged between 1-1.2 l s^{-1} ha^{-1}, as previously stated. Thus, the application of the trained ANN obtained would be limited to regions with similar networks' properties, where the water source was surface water with the same simultaneity index and design demand. The method could also be applied to other areas with different network characteristics, but the ANN would have to be defined again using networks typical from the region to be analysed. Future research could be focused on the analysis of networks from different regions and the quantification of MHP's benefits in the whole Andalusia.

The results obtained in this research showed a mean R^2 of 0.63, which reached its highest value (0.74) in the third fold of the cross validation. The potential predicted for provinces accounted 21.05 GWh found in an irrigated surface of 163,472 ha during 2018. The potential found per irrigated unit area was 0.129 MWh ha^{-1}. This compares well with the measured potential of 0.167 MWh ha^{-1} in the 18 detailed hydraulic networks. The difference between the observations and the predicted values was of 0.038 MW ha^{-1}. Comparing the MAE corrected potential, the energy recovery per unit irrigated area varied from 0.116 MWh ha^{-1} to 0.145 MWh ha^{-1}.

The energy recovery potential per unit irrigated surface indices found in previous research, in MWh ha^{-1}, varied as 0.65 and 0.08 (García Morillo et al. 2018; Pérez-Sánchez et al. 2016) and 0.10 and 0.11 in Chapter 4 and Chapter 5 respectively. The results obtained in this research remained within acceptable values when compared to these previous ratios. If the index extracted from the 18 networks would have been used to predict the existing potential in the irrigated surface for both provinces, 7.5 GWh more would be estimated. Thus, the method proposed in this research, is able to go beyond the simple assumption of a linear trend between the irrigated surface and the existing potential, through a deep learning process and the introduction of other proxy variables. In addition, the correction factor of 0.7 was used to limit the predicted output to show just energy recovery potential which was economically viable. Therefore, the surface taken into account in Seville and Cordoba could be increased if the economical parameters used in the methodology developed Chapter 4 changed (i.e. economical savings per energy unit, installation costs, grants, etc).

On the other hand, it would be very complex to find points with existing potential within the irrigation sector where the energy recovered could be directly sold to the grid, stored or used for direct purposes, such as pumping. For either use, the installation costs could be importantly increased, making too many of the plants not economically attractive for investors. MHP solutions together with storage systems could be a potential way to apply the energy recovered at points where energy is required. Nevertheless, costs and logistic make this solution unviable currently for those points where no energy is needed. An attractive use for recovering energy could be at farm levels, where farmers with no access to electric grid tend to use diesel generators if some energy consumption is required. Adopting this alternative would reduce the amount of energy to be recovered using MHP as turbines located at farm level will inevitably have less flow and pressure available than those located higher up in the pipe network. However, this could still be considered as a potential measure to reduce the energy dependency of irrigation networks.

Comparing the energy savings obtained by MHP with other measures for improving the energy dependency in irrigation, the results obtained here showed that MHP could be an important solution. Furthermore, it could also be applied in tandem with the different energy saving measures previously highlighted in Chapter 2. For example, irrigation scheduling together with MHP could be a potential solution to improve energy dependency. Concerning the photovoltaic solution, this is limited for power production just during the sunlight hours. In big irrigation infrastructures, pumping using photovoltaic energy is considered as a potential solution to reduce the energy dependency. The addition of MHP to this solution in the networks could lead to an important reduction of the energy consumption in this sector. Coupling both technologies could be of special interest for future research.

6.5. Conclusion

Sustainable development requires clean energy sources for GHG emissions to be reduced in the short term, and completely avoided in the long term. Hydropower accounted for almost 40% of the total renewable generation in the EU (European Commission 2018). Nonetheless, micro hydro resources are not very well exploited yet. It is first necessary to conduct a large geographical scale assessment of these available resources in different sectors, quantifying the existing potential and its intrinsic environmental and economic benefits, in order to allow targeted investment in micro-hydropower.

Linear models, single and multivariate, and ANNs were studied in this research for predicting the MHP energy recovery in pressurised irrigation networks. Three variables that could be easily obtained for the different irrigated areas in many regions around the world were used as input data, through which the energy recovery potential was predicted. Irrigated surface area of pressurised systems, irrigation requirements (directly related to the crops and the agro-climatic parameters), and mean slope of the area were the input variables. Inputs and outputs, were first obtained for 18 irrigation networks, using detailed hydraulic models, where 177 potential MHP installation (as observations), composed the database of economically viable sites.

ANNs showed the best results and was used for large-scale prediction in two provinces in Andalusia. Using the ADAM optimisation algorithm and minimising the mean squared error as objective function, the network was able to predict the energy recovery potential with a R^2 varying from 0.46 to 0.74, with an average value of 0.63. The minimum MSE varied between 320.9 and 445.8 MWh, with a mean value of 383.3 MWh. Two hidden layers with 26 neurons in the first and 18 in the second composed the network's structure. A total potential of 21.05 GWh during 2018 for the regions of Seville and Cordoba, in Southern Spain, was predicted. Important environmental and economic benefits would be linked to this energy recovery, with more than 5,000 t eCO_2 per year and more than 12% of reduction in energy costs in irrigation. A reduction in energy consumption in the agriculture sector of this magnitude could have significant impacts on food production and climate change.

7 REAL-SCALE IMPLEMENTATION

7.1. Introduction

Various solutions have been proposed to improve the energy efficiency of the sector. These were related to either the operational management of the networks, optimisation of the pump stations, optimisation techniques, or the use of renewable energies (Abadia et al. 2010; Cobo et al. 2011; Díaz et al. 2009; Fernández García et al. 2014a; García Morillo et al. 2018; González Perea et al. 2016; Jiménez-Bello et al. 2010; Lamaddalena and Khila 2012; Mérida García et al. 2018; Moreno et al. 2010a; b, 2007a; Pérez-Sánchez et al. 2016, 2017). These studies were focused on the improvement of the energy efficiency in irrigation pipe network distribution systems, attaining energy savings of around 30% in several cases or even the total avoidance of fossil fuel sources for the energy supply. However, there are other locations within irrigation systems as a whole where energy could be saved, such as at farm level. In many cases, the required energy at farm level is produced in situ, using diesel generators to feed the different devices required during irrigation due to the lack of electric grid connections in rural areas. These cases increase the energy dependency of the activity while also increasing the air pollution and climate change contributions.

Renewable energies could be a viable alternative to replace farm-level diesel generators, reducing CO_2 emissions and local air pollution, whilst bringing electricity to remote places with no grid connection. The issue of energy supply in remote places is a universal sustainability challenge for the agricultural sector, and MHP could be applied to supply this local farm-level energy demands sustainably. The excess pressure at hydrant- or farm-level in some cases would make the generation of MHP while irrigating and its consumption on site, possible. The total replacement of diesel generation would lead to significant environmental savings, taking advantage of existing hydraulic resources to supply the energy demanded. Moreover, using PATs would make MHP an even more attractive solution. Some authors referred to cost-effectiveness as an advantage of PAT technology when compared to traditional hydraulic turbines for small power output schemes (Carravetta et al. 2014b; Fecarotta et al. 2014a; Lydon et al. 2017a). Previous investigations studied the theoretical or experimental performance of PATs installed in labs. However, no research was made of a PAT operating under actual real world irrigation network conditions.

This chapter presents new knowledge for the design phase of an MHP plant at irrigation farm level. The chapter presents new knowledge on MHP operation in irrigation networks, informed by the first data on actual performance of an MHP plant, installed in a pressurised irrigation network and constructed at farm level. A PAT was designed to replace a diesel generator and to feed the local electrical devices used during irrigation. The plant was designed to take advantage of a small amount of head from the existing excess pressure in the network and a small amount of flow from the farmer’s total demand. The considerations taken into account during the design were focused on ensuring no effect on the farmer’s activity while guaranteeing the energy supply. The assessment of the potential economic and environmental benefits were first carried out, estimating the farm irrigation time and the plants operation length. A study of the return on investment was made, predicting the payback period of the plant. Both, design benefits and predicted investment return were then contrasted with the actual performance results measured during the 2019 irrigation season. The actual performance of the plant was recorded using a remote monitoring system implemented at the plant, which allowed the analysis of the plant working under actual conditions. The novelty of the work resides on being the first research conducted on the actual operation, design and performance of a pump-as-turbine installation in a real working water network. Lastly, an analysis of two PAT regulation schemes (hydraulic and electric), and the global efficiency of the plant were carried out. The results obtained in this research could lead to a more efficient plant designs and a better understanding of PAT performance working under actual conditions, thus improving the plant power and global efficiency, and sustainability of energy sources applied to the agriculture sector.

7.2. Study area

A pilot PAT power plant was designed, and subsequently constructed at a farm located within the left bank of the Genil river irrigation district (GMI), in Southern Spain. The total area irrigated in this district was approximately 6400 ha with a predominance of citrus and almond crops, although other crop types could also be found, including walnuts and olive trees. The hydraulic infrastructure is composed of a pressurised branched network with pipe diameters that varied between 75mm and 1200mm, supplying water to a set of 88 hydrants distributed around the district. The network is fed by two sets of water reservoirs and decanting pools. The set of main reservoir and decanting pools, shown in Figure 4-2, feed the pipes that reaches the farm and amounts to a storage capacity greater than 1 hm^3. This set is fed by a pumping station with a power capacity installed over 1MW, which usually works during the night period, when the energy tariff is lower. The service pressure or minimum head required at hydrant level was 35m. The network was designed to supply 1.2 $l\ s^{-1}\ ha^{-1}$ on-demand (24 h per day) under the hypothesis of 100% simultaneity (i.e. all hydrants simultaneously open).

The aforementioned farm was fed by a single hydrant, irrigating a surface of about 170 ha distributed in three plots, with walnut as the sole crop. A main 400mm diameter steel pipe formed the water distribution system feeding the irrigation infrastructure within the farm. Three smaller distribution pipes were also present and these had a diameter of 200mm distributing water around the plots. Three pressure reducing valves (PRVs) were installed in these distribution pipes, as drip irrigation was practised at the farm and low heads were required in the inlet of the drippers. A location map and the layout of the irrigation district can be seen in Figure 7-1, as well as the farm, highlighted in dashed green.

The farm relied on a 6kVA diesel generator for energy consumption due to its location, isolated from the grid. Energy demands included two fertigation pumps, 78 electro-valves for a water filtering system (irrigation water is untreated), and an air compressor for maintenance operations. The maximum local energy requirements, considering all of these devices requiring power at the same, was 3.6 kW.

The mean annual rainfall and evapotranspiration over the last ten years (2009-2018) amounted to 641.8 mm and 1,328.6 mm respectively. The monthly average evapotranspiration and rainfall distribution for this period can be seen in Figure 7-2.

Different pictures of the farm crops and installations, as well as the aerial view of the reservoir feeding the network can be seen in Figure 7-3. The existing facilities and devices at the farm shown in Figure 7-3 were: i) Operating, storage and maintenance area (Figure 7-3b); ii) 2m x 2.4m concrete chamber keeping the three hydrant's valves (green valves in Figure 7-3); iii) Filtering system composed by the 78 electro-valves aforementioned (system in red in Figure 7-3); iv) PRVs at the output of the hydrant to control the inlet pressure at the drippers (Figure 7-3c).

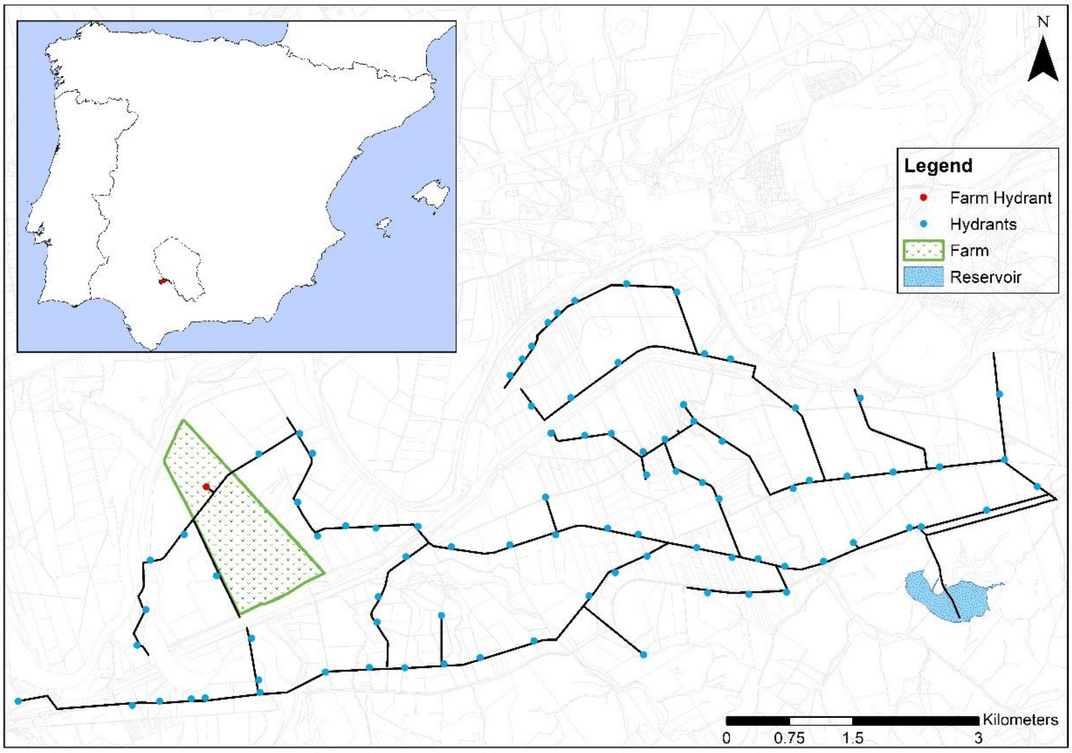

Figure 7-1. *Location and layout of the network and farm where the plant was constructed (Genil river irrigation district, Southern Spain).*

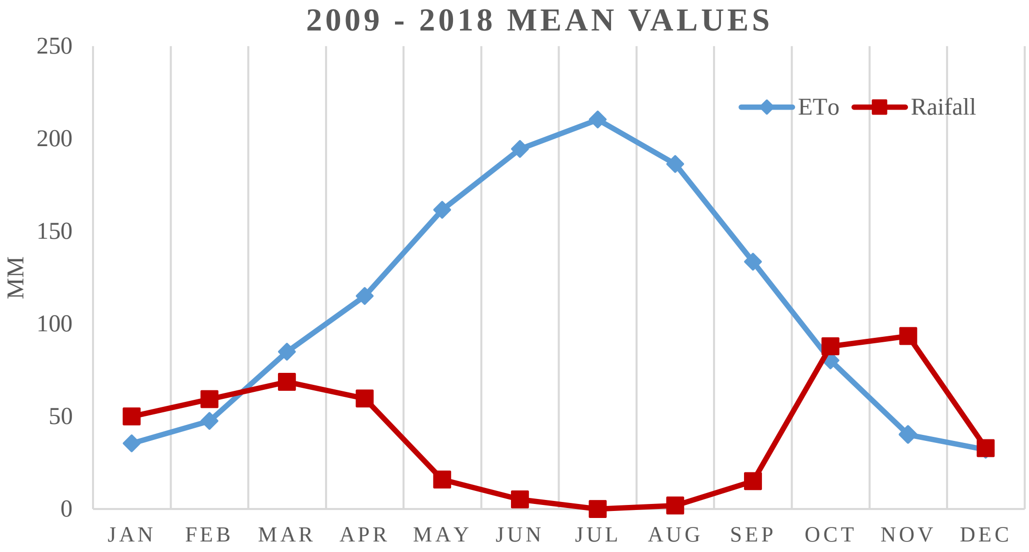

Figure 7-2. *Average rainfall and evapotransporation between 2009-2018*

Figure 7-3. *Aerial view of the reservoir feeding the irrigation networks and different views of the farm prior the PAT installation. a) Reservoir that feeds the irrigation network; b) Operating, storage and maintenance area; c)PRVs at the output of the hydrant; d) Filtering system located within the operating area; e) Diesel generator used at the farm; f) valves composing the hydrants inside of the concrete chamber; g) walnuts irrigated downstream of the hydrant.*

Although walnut is not a typical crop cultivated in this part of Spain, the study farm started cultivating it in 2016. Since then, the farmer main challenge has been to reduce environmental impact, being fundamental to maintain the balance generated through the harmonious relationship between the society and the nature around it.

The farmer manages the full production of the nuts, so that it controls the entire activity process, from selection and planting, to delivery. Being present throughout the value chain allows the application of good practices in the sector and harnessing, which leads to greater efficiency in the production of nuts.

As part of this environmental compromise mentioned, the farmer agreed to build the experimental plant described in this chapter. The plant eliminated a diesel generator, which contributed significantly to the air pollution of the surrounded area. Thus, the farmer would decrease the eCO_2 related to the nuts production down to null through recovering the energy previously dissipated at the PRV showed in Figure 7-3c.

7.3. Methodology

7.3.1. Hydraulic modelling and flow and head predictions

An EPANET hydraulic model of the whole network shown in Figure 7-1 was developed (Rossman 2000). The model was developed using several input files described in Chapter 5: i) A dwg file with the structure of the network, which was gathered from the irrigation district; ii) database including the properties of the network (pipes, materials, diameters, consumption points, design properties, such as flow requirements in l/(s ha)). This data was collected from the irrigation network design project, available at the main office of the irrigation district; iii) Crops distribution for each hydrant; iv) and digital elevation model of the area to extract the nodes' elevation. The 10m elevation model was available online (Instituto de Estadistica y Cartografia, Junta de Andalucia).The model enabled the analysis of the existing working conditions in the farm along the entire irrigation season. Modelling was conducted as described in detail in Chapters 4 and 5. Obtaining accurate flow and head distributions for the network was important since the operation of PATs are sensitive to fluctuations in flow and head. Inaccurate flow predictions could result in significantly underperforming PATs. Furthermore, measurements of flow and head in irrigation networks are not commonly available and were not available at this network.

For the different flow values at this location, the three plots irrigated by the hydrant were included individually in the hydraulic model, taking into account the areas irrigated and the base demand of each of them. The flow and head distributions were predicted for the issue hydrant using the methodology developed and validated in Chapters 4 and 5. Summarising, this methodology considered all possible combinations of the 88 open/closed hydrants to obtain the flow occurrence probability, and thus occurrence time, for every possible flow applying the Bernoulli Experiment.

The Bernoulli Experiment was run in the hydraulic model of the network integrating the EPANET engine into Python (v. 2.7.15) through EPANET's programmer toolkit. Once the Bernoulli Experiment was run, the flow and head distributions were obtained, thus enabling the analysis of the flow and head conditions during the entire irrigation season. This allowed the variation in excess pressure at the farm to be predicted. The occurrence probability for each combination of flow and head was calculated using the mass probability function (see Equation (7.1)). The cumulative probability function was then obtained and the exceedance probability for every flow and head was estimated.

$$p(X_i) = \frac{n_i}{N} \tag{7.1}$$

Where *X* refers to each of the variables (flow and head); *n* is the number of times that each value was obtained; *N* is the number of simulations runs; *i* refers to each of the values of the domains of the variables.

7.3.2. Design approach and performance prediction

The energy requirement prior to the plant construction was supplied by the diesel generator previously mentioned. The main aim of this PAT installation was to replace this completely, therefore avoiding the use of fossil fuelled generation. The employment of a PAT together with an energy storage system would allow the full replacement of the diesel generator. This system must be able to supply the required energy even when the farmer was not irrigating (and therefore no flow was occurring at the turbine). Energy storage devices were used to store energy when excess was available and supply it when energy was required outside of irrigation occurring. This solution involved saving 100% of diesel consumption and GHG emissions. The theoretical analysis conducted for the plant design used average climatic conditions from the last 10 years (2009-2018) to account for evapotranspiration and hence water demands. The PAT was installed in a bypass scheme, diverting only the flow required to cover the maximum energy demand of the farmer (3.6 kW). The PAT was selected based on four considerations: i) operability of the farm; ii) maximum energy requirement; iii) best efficiency point (BEP) of the PAT; and iv) economic and environmental benefits.

7.3.2.1. Irrigation operability

One fundamental aspect that the PAT design took into account was the extent to which the operation of the farm would be affected by the presence of the turbine. The activity of the farmer could not be altered when the PAT was installed, as the primary function of the network (irrigation), must not be affected by hydropower production. There is a minimum head required at hydrant level for the proper functioning of the irrigation infrastructure. Hence, the head after the PAT installation had to be at least equal to this service pressure. In order to ensure no effect on the irrigation network operation, backup energy systems were also required to feed local demands in case of insufficient available head for energy production. As the main purpose was the total replacement of the diesel generator and due to the lack of grid connections, energy storage systems could be used as backup.

7.3.2.2. Power requirements

The energy requirements could vary depending on the activity of the farmer and the stage of the irrigation season. Therefore, the nominal power was fixed to always ensure the maximum energy demand (3.6 kW). Nevertheless, as the energy demanded could vary, the power produced could be higher than the energy demanded on a regular basis. Two 4kW resistors in series were installed to dissipate the energy recovered and not used by the farmer in those periods where not all the power was required. A resistor is an electrical device that can dissipate power as heat.

7.3.2.3. BEP selection

Regarding the BEP, the flow demanded and available head at the hydrant suffered significant fluctuations, greater than in other types of water network. Therefore, the occurrence probability of flows and heads were analysed, finally selecting the BEP that ensured the energy supply along the irrigation season or, in case of lack of flow or head, during most of the irrigation season, including those periods of intensive demands, concentrated in June, July and August.

7.3.2.4. Economic and environmental savings

The payback period was an important variable to consider the investment risk in designing the MHP installation within the irrigation sector. These networks only work during concentrated periods from approximately March to October and with high variability within the irrigation season, thus limiting the operation time of the plants and their cost-effectiveness. To carry out the economic analysis, the economic savings generated by the plant and its cost were evaluated. The savings depended directly on the annual volume of diesel saved. The diesel volume consumed per unit time, the cost of diesel per litre, and the operation time of the farm were hence required.

The diesel consumption per working hour was obtained from the technical sheet of the generator, fixed at 1.2 l h^{-1}. The operation time during the season depended on the BEP of the PAT design and its occurrence probability. This was previously estimated for each flow and head. The seasonal volume consumed was obtained multiplying the unit consumption by the operation time. A mean cost of €0.77 per litre for the 2019 irrigation season was obtained from the records of agricultural diesel prices for that period in Spain (Expansion: Datos Macro 2019). The savings were then estimated multiplying the seasonal diesel volume estimated by the mean cost of the diesel.

The cost of the PAT and civil and electric works were estimated using the model proposed in Chapter 4. This considered the cost model for electromechanical devices (PAT + generator) developed by Novara et al. (2019) and civil works costs for MHP plants in irrigation networks depending on the nominal power of the PAT. The cost of the backup system and heatsinks were also taken into account.

Another key aspect to be considered was the avoidance of GHG emissions. The environmental benefits would be related to the existing supply system, in the form of emissions saved. Thus, to estimate the emissions, two parameters were required: i) the diesel volume used for the whole season; and ii) the emission factor for diesel generators. The Spanish emission factor for fixed diesel generation equipment was used (2.868 kg eCO_2 $l^{-1}$for diesel type C) for 2018 (Ministerio para la Transicion Ecologica 2019). The amount of emissions savings was then calculated multiplying the seasonal volume of diesel employed by the emission factor.

7.3.3. Installation and Performance measurements

The final plant installation was completed following the guidelines given in the previous section but with small differences. The final plant had a 4 kW nominal power output and was composed of a PAT installed in a 150mm bypass with a set of four batteries connected in series. The PAT installed was a KSB INLINE 080-B pump, whose BEP as a turbine corresponded to 30l s^{-1} and 20 m.

The theoretical and actual power and BEP of the PAT differed slightly. This was one of the limitations reported in Chapter 4 for the methodology developed, where the optimum theoretical PAT recommend by method must be matched with the closet actual PAT available on the market. Other properties of the PAT were an 80mm diameter inlet and outlet flange and a 174 mm impeller. The nominal speed of the device was 1800 rpm. The generator used was a Eura Drives EVPM model with a four poles permanent magnet motor, and a nominal power of 4kW. The nominal rotational speed was 1500 rpm. The maximum global efficiency of the plant was 68%. The batteries employed corresponded to the monoblock sealed AGM model MEBA12-220 from the manufacturer ME. These had a voltage of 12V, an Ah capacity of 220Ah, and a total capacity of 10.56 kWh. The head drop, power and efficiency curve as per the flow rate can be seen in Figure 7-4.

The working conditions of the PAT were set using both electric and hydraulic regulations (ER and HR) (Carravetta et al. 2014a). ER and HR were used to control the operation of the PAT to be close to its BEP for the majority of its operation. In practice, both control systems are not required and the plant could work using just HR. However, the experimental aim of the pilot plant allowed comparison of both control methods. To achieve this a variable speed drive (VSD) and a pressure reducing valve (PRV) were installed. Both schemes had been previously compared by other authors theoretically, concluding a slightly better performance of the ER against a more economic option in case of HR (Carravetta et al. 2014a).

Firstly, the PRV was operated completely open, therefore allowing to the VSD to regulate the rotational speed on its own, depending on the inlet conditions at the PAT. To test the HR, the PRV was set using a certain backpressure, thus regulating the PAT inlet conditions, which varied depending on the conditions available at the farm. The charge regulator installed to test the ER was a Schneider Electric model Conext MPPT 80 600. The installation scheme can be seen in Figure 7-5.

In addition to the PAT, generator and the energy storage system, two solar panels were installed with a total nominal power of 660W. The model used was the Amerisolar AS-6P. The aim of solar panels was to maintain the charge level of the batteries in those periods outside of the irrigation season (October to March). This would avoid the total discharge of the batteries leading to their damage or failure over the long term.

A monitoring system was also installed at the plant in order to record the working conditions and the actual results obtained. The system was based on a GPRS datalogger, which allowed remote access, displayed live data, and stored the data monitored in historical files. The datalogger installed was a Hermes M100 combined with the model M120, from Microcom. The system used a SIM card to send the data to the ZEUS server, a cloud provided by Microcom where the data was stored and displayed (see Figure 7-6).

The devices used for the data monitoring included: a Hidroconta ultrasonic flow meter; two pressure gauges recording the inlet and outlet pressure at the turbine (Danfoss model MBS 1700); the voltage of the batteries was monitored directly in one of the inputs of the datalogger; power generated by the turbine and consumed by the local irrigation devices were also registered in the datalogger. These variables were registered every 30 seconds, amounting to a high definition data set, which allowed the quantification of the actual benefits achieved during the irrigation season in 2019 and the plant performance.

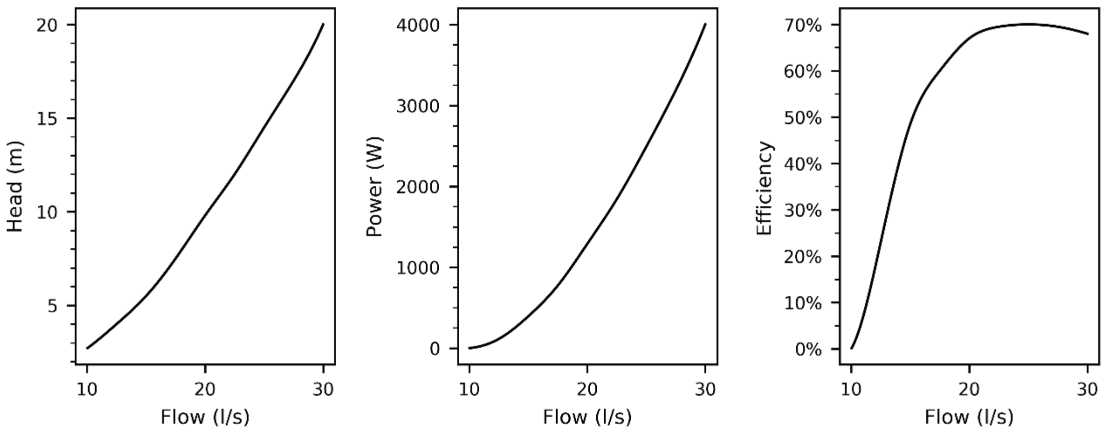

Figure 7-4. *Head drop, power generated and global efficiency curves of the plant depending on the flow rate.*

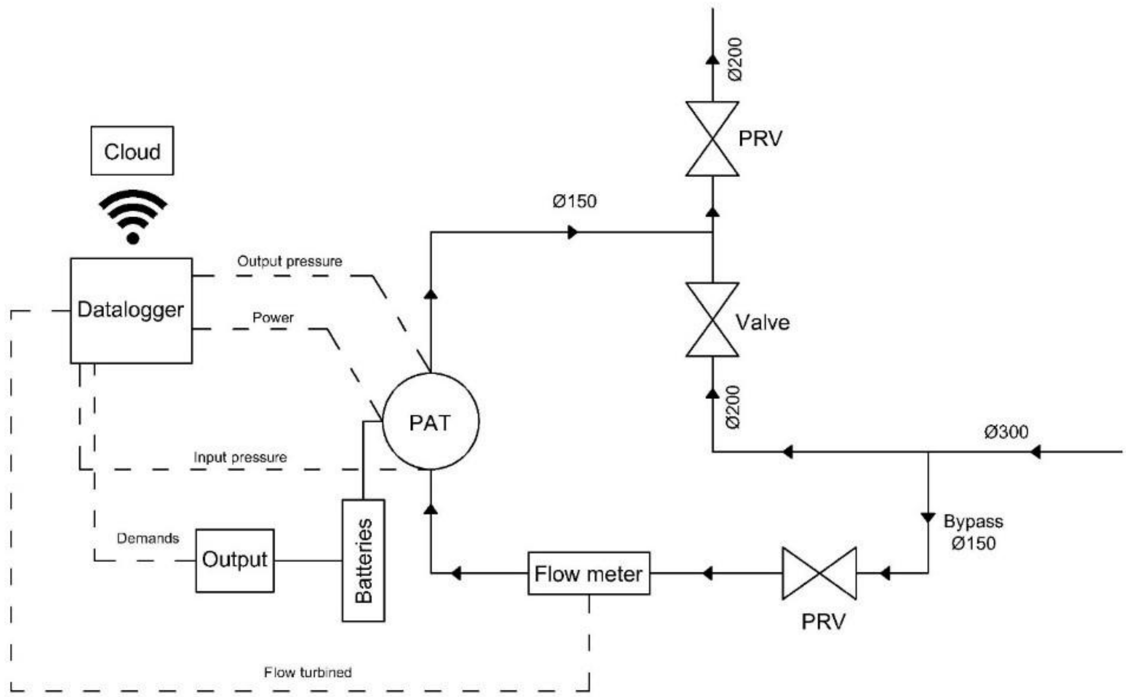

Figure 7-5. *Plant scheme, including the device connection to the datalogger in dashed.*

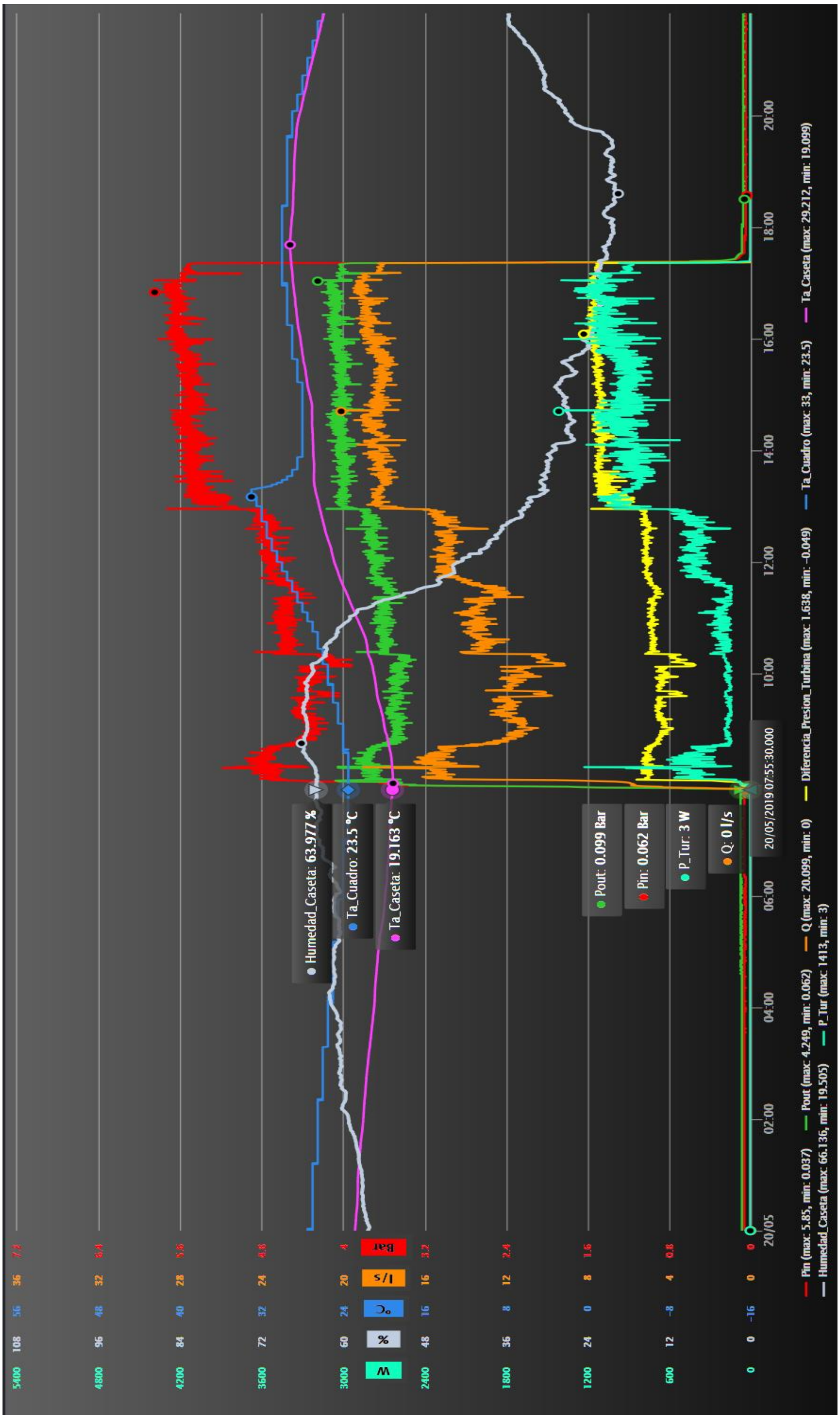

Figure 7-6. *ZEUS remote monitoring display*

7.3.4. Plant construction and testing

There was a main barrier found during the design phase related to the irrigation activity of the farmer: any work affecting the water network had to be done out of the irrigation season in order to not affect the crop irrigation and the farmer's annual yield. The MHP plant was constructed January and April 2019 after confirming the starting date of the irrigation season with the farmer, set up at the end of April. Figure 7-7 showed the different elements and devices of the plant after finishing the construction. The 4 kW PAT installed in the bypass is presented in Figure 7-7a. The existing chamber and the extension, as well as the solar panels and the resistors (covered by the aluminium case) can be observed in Figure 7-7b. Two different views of the bypass made to install the PAT can be seen in Figures 7-7c (connection downstream the turbine) and 7-7d (output of the turbine). Figure 7-7e showed the bench of batteries, where the energy is stored. The PRV required for the HR, installed upstream the PAT, is shown in Figure 7-7f. The flow meter installed in the bypass, upstream the PAT, to measure the flow turbined can be observed in Figure 7-7g. Finally, the protection cover for the datalogger, charge regulator and VSD is shown in Figure 7-7h.

Due to the space limitation of the chamber where all the hydraulic devices were installed, an extension was made next to this chamber to keep all the control and electric devices (VSD, batteries, charge regulator…).

After all the civil works were completed, the PAT installation and electrical and monitoring devices connection was carried out. The plant was tested on the 28th of March 2019, giving the results shown below:

- Turbine Output Voltage: **389V**
- Turbine Output Intensity: **12,5A**
- Turbine power production: **4.86 kW**

Figure 7-7. *Different views of the MHP plant, showing the PAT, PRV, bypass connection, monitoring system (flow meter) and regulation chart.*

Once the electromechanical devices were tested and checked that they were operating correctly, the plant started operating two weeks later, with the beginning of the irrigation season for the farmer. However, an issue related to the monitoring system arose, which led to missing the data record of the energy produced and irrigation time in April. This is further discussed later in the thesis.

7.4. Results

7.4.1. Performance Prediction prior to installation

The irrigation period for the farm was estimated to be carried out between April and September. Considering the existence of the three different sectors irrigated by the selected hydrant as individual hydrants, eight combinations of open/closed hydrants were possible within the farm. It was stated in Chapter 4 that the number of monthly simulations should be at least double the possible combinations in order to increase the likelihood of every possible combination to occur. Nonetheless, the minimum pressure found at the hydrant at the farm when all the hydrants in the remainder of the district (87 hydrants) were open (100% simultaneity) was 32m. This was a little lower than the required head of 35m. This fact meant that no head could be recovered by the PAT under these conditions. Thus, the amount of combinations of open/closed hydrants for the network of the entire irrigation district had to be examined to study the head conditions at the farm hydrant in more detail.

The required number of combinations considering the 88 hydrants in the full distribution network was up to 5.8×10^{23}. However, the number of simulations to be run had to be reduced, since it was not possible to carry out this number of simulations due to limitations of computational resources. Thus, the Bernoulli Experiment was run employing three million simulations, for which the flow and head values were predicted.

To inform the design of the PAT, the flow was predicted at the inlet pipe, and the pressure at the main hydrant was also predicted. This data can be seen in Figure 7-8a for the whole irrigation season. The minimum head predicted at the hydrant was 35m, which appeared just once out of the three million simulations. This head occurred when around 90% of the farmers in the district were simultaneously irrigating and reflected how for those intensive irrigation periods there was a small probability of not having any excess pressure available. This issue made the inclusion of the energy storage system necessary as backup to ensure the reliability of the energy supply. Although the occurrence probability for those high simultaneity events was predicted to be low, as shown in Figure 7-8b, the main aim of the plant was ensuring the energy supply, fully replacing the diesel generator. The minimum flow demanded was estimated to have an exceedance probability of 73% (see Figure 7-8b), which means that the farmer would irrigate for around 73% of the time available between April and September.

The PAT design objective was to ensure the maximum energy requirements of the farm were supplied. Thus, the nominal power was fixed at 3.6 kW. The green line in Figure 7-8a represents the flow and head BEPs for all theoretical PATs which are predicted to return 3.6kW of power under the flow and head conditions predicted at the farm and considering a 55% global plant efficiency. In order to have the maximum power requirements each time that the farmer irrigated without affecting the activity, the nominal flow through the PAT was fixed as the minimum flow estimated to be required by the farmer, 25.4 l s^{-1}. For this flow value, the excess head required to return 3.6kW was approximately 26m.

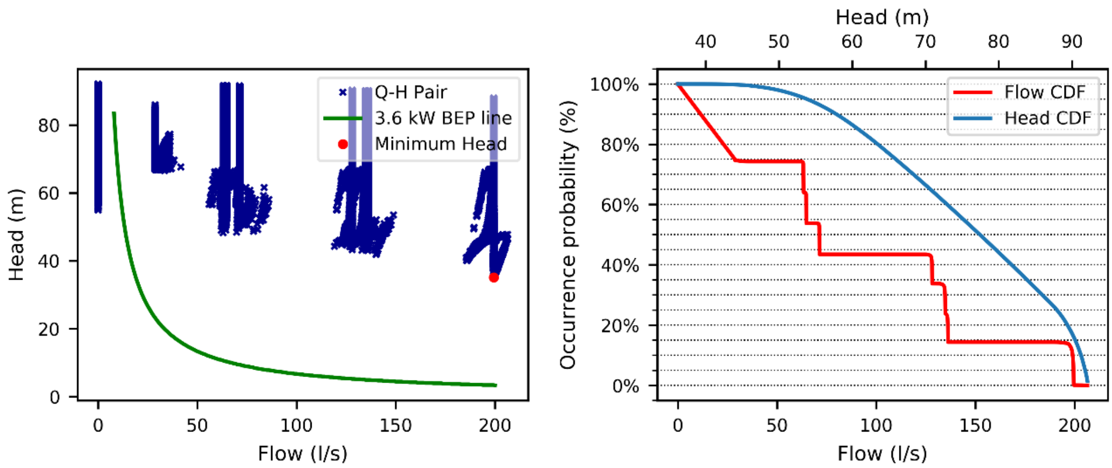

Figure 7-8. *a) Set of flow-head pair of points obtained for the Bernoulli Experiment, best efficiency flow-head line returning 3.6kW and minimum head found in the simulations; b) Cumulative distribution functions for flow and head at the farm.*

The farm irrigation time was estimated at around 73% of the irrigation season, using the flow prediction methodology. The minimum head that allowed the energy production was present 99% of the irrigation time. Thus, the energy storage system would ensure the supply in those periods where no head was available for MHP production. Translating this into time, around 40 hours were found where the pressure would not be enough to allow the energy recovery. The size of the energy storage system was defined according to this lack of head found in the very intensive irrigation periods. This head absence was predicted to occur during small intermittent periods in

July and August. Considering the most intensive irrigation periods concentrated in one week in July and one week in August, the time was daily distributed along these two weeks, rather than distribute it for the two months, which would return a smaller batteries capacity. Thus, around the daily lack of head was estimated in around two hours and half for these two weeks. Therefore, the backup system was designed to have capacity for around two and half hours of maximum energy requirements. This approach was done conservatively, in order to avoid the absence of energy at the farm, but not increasing the cost significantly, as no actual information of head was available. Once the size of the storage system was defined, the installation cost was then estimated.

Electromechanical devices, civil and electrical works, energy storage system and heatsinks to dissipate the excess energy produced, and design costs were included in cost estimations. The energy storage system and energy dissipation costs were accounted for using market prices, and design costs were assumed to be 20% of the other costs. The final cost was estimated at €21,318.

The operation time at the farm was estimated at up to 3,199 hours per annum. During the irrigation time, in previous years the diesel generator was working. With this operation time, the annual diesel volume required by the generator was estimated at 3,839 litres. The economic savings were therefore predicted as approximately €2,956 per year, achieving an attractive payback period of 7.2 years. Furthermore, the environmental savings which could be achieved was estimated at up to 11 t eCO_2 per annum.

7.4.2. Installation and Actual Performance Measurements

The plant was constructed during March 2019, starting its operation in April 2019 at the same time that the irrigation activity at the farm commenced. The final cost of the plant was €22,350, which included the devices for the plant to operate correctly and ensuring the energy demand.

During the first month of operation, the monitoring system was not functioning fully and the data during April 2019 was not recorded. The irrigation activity in 2019 lasted until the end of September at the farm. The monitoring system allowed remote access to the live data, daily summaries or historic register (see Figure 7-9), which permitted a constant oversight of the plant. The total operation time recorded between May and September was 2,443 hours, to which the irrigation time in April should be added (but was not recorded). The total energy demanded in this period amounted to 222 kWh, which was supplied entirely by the pilot plant. The diesel saved was estimated at 2,932 litres. Considering the mean diesel cost for the 2019 irrigation season, the economic savings were €2,258, not including activity in April.

The energy demanded by the farmer between May and September and the energy produced by the PAT can be seen in Figure 7-10. It can be observed how the production was similar to the demand most of the time. Regarding the energy demand of the farm, it can also be seen that this was generally lower than the maximum energy considered (3.6 kW), although it was demanded at some stages of the irrigation season.

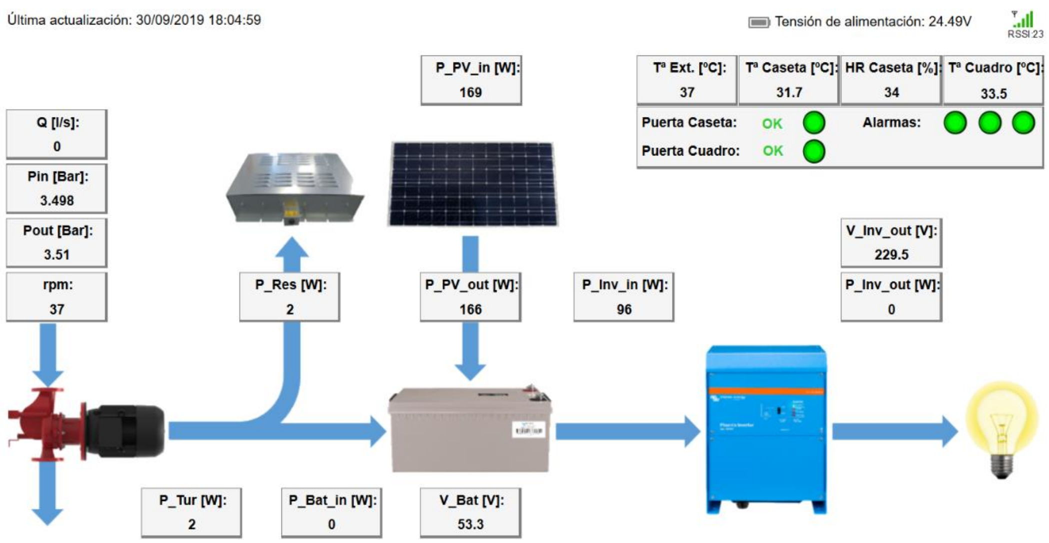

Figure 7-9. *Plant synoptic shown at the monitoring platform displaying live data.*

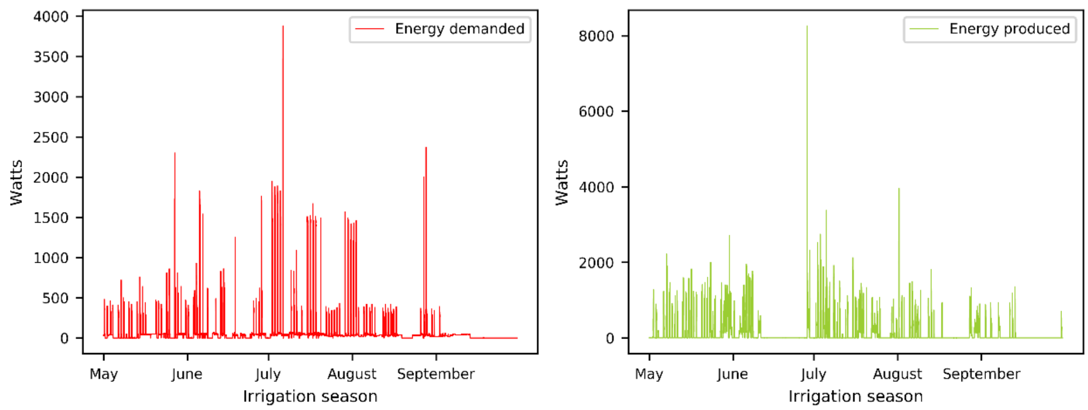

Figure 7-10. *Energy demanded at the farm and energy produced by the PAT during the 2019 irrigation season.*

Considering the plant operations, both hydraulic and electrical regulation were tested. During the first part of the irrigation season (May and June) the plant operated using just the VSD (ER). From July until the end of the season, HR was used, setting the PRV installed upstream the PAT. Due to the seasonality of the activity and the variation of the weather and crop irrigation requirements, the flow fluctuations along the season were quite significant. This variability in the working conditions provides one of the main drawbacks of using PATs in this setting, as their performance can be greatly affected in the absence of a regulation system.

Using ER system presented problems when the variations in pressure were high, due to the lack of devices controlling the inlet conditions. However, the HR system regulated the inlet pressure using a PRV upstream, thus stabilising the operation of the PAT. This difference can be seen in Figure 7-11, in which the PAT flow, inlet and outlet pressure were represented in May and July.

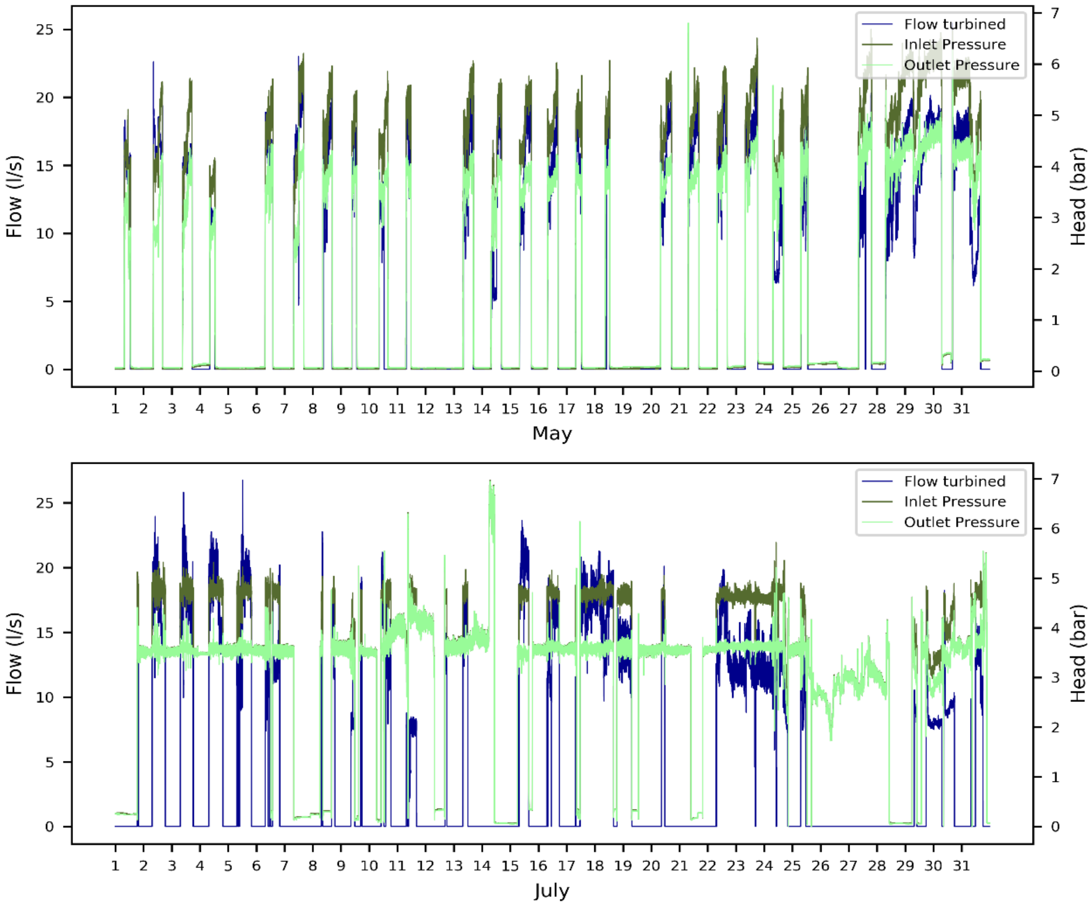

Figure 7-11. *PAT working conditions for ER (May) and HR (July) registered during the irrigation season.*

The fluctuations of the inlet pressure found in May were larger than in July, therefore affecting the working conditions of the PAT as well as its rotational speed. Thus, the employment of ER in networks with large fluctuations would need to be accompanied by hydraulic control devices to regulate the inlet conditions in order to maintain the integrity of the installation. This fact would increase the plant cost, hence affecting the investment viability. Therefore, HR schemes on their own seem more appropriate for plants at farms in large pressurised irrigation networks.

Considering the actual cost of the plant taking into account only the required devices for the plant operation, the payback period was estimated at 9.9 years, i.e. excluding data monitoring system. Moreover, 100% of the GHG emissions were avoided, which were close to the 8.4 t eCO_2. If the predicted /irrigation time for April was used to quantify the whole season benefits, 191 hours more should be added to the time recorded. Thus, the emissions and diesel avoided raised up to 9.1 t eCO_2 and €2,433, dropping the payback to 9.2 years. A summary of the results obtained at the design stage and the actual results recorded can be seen at Table 7-1.

The annual volume applied to the crops are not always exactly the same as the theoretical irrigation requirements and usually farmers apply deficit irrigation. This effect is common in the area and can be explained by factors such as limitations in the water allocation by the water authority or the irrigation costs. This explains the difference between the number of hours of actual and theoretical irrigation in some months of the year.

Table 7-1. *Summary of the theoretical and actual results.* actual operating time in April not recorded and theoretical value is used in calculations of total time, costs and savings.*

	Month	**Theoretical**	**Actual**
Operation Time (hours)	April	191.2	(191.2)*
	May	644.5	420.4
	June	682.0	386.3
	July	684.1	689.0
	August	605.5	642.0
	September	391.7	305.2
	Total	3,199	2,443
Savings	Cost (€)	21,318	22,350
	Litres	3,839	2,932
	€	2,956	2,258
	t eCO_2	11.0	8.4
	PP	7.2	9.2

7.5. Discussion

Several measures have been proposed in literature and tested in practice in order to reduce the energy dependency of irrigation networks achieving important results in some cases. However, most of these studies analysed the energy dependency of the irrigation distribution network, which is the largest overall energy consumer in an irrigation district. However, these have not considered the energy requirements at farm level. Farms often require energy to carry out the irrigation activity on the farm, either for water filtering, automatic fertilisation or boosting water pressure. In addition, these farms can often be remotely located, not having access to the electric grid, and therefore necessitating the use of other sources to cover the energy demand, most commonly a diesel generator.

For this particular pilot installation, the irrigation requirements increased as the irrigation season went on, therefore incrementing the farm operation time. This fact was also noticed in the data monitored. During the beginning of the season, the farmer mostly irrigated during the daytime, thus not demanding energy at night. This trend then changed for those hotter periods between July and August, in which long night periods of energy demands were also recorded. Analysing the amount of energy requested for day and night time, a considerable difference was found. While it is true that during the day time the demand was significant, oscillating between 1 and 2 kW in most of the cases, and reaching peaks of almost 4 kW for some hours, it dropped for the night period to around 40 W. This was related to the habits practised by the farmer. During the day time, energy was used for one or two fertigation pumps, for the filtering station and for an air compressor, according to the farm requirements. Most of these devices were not used during the night time, typically only energy the filter station was required, which consumed a small amount of energy. This energy was previously supplied by the 6kVA diesel generator, which worked for the entire night time just to feed this small output. Thus, a significant amount of diesel consumption was removed, generating valuable economic and environmental savings.

In addition, as just a small amount of energy was demanded during the night, the bypass where the PAT was installed was closed as the batteries were able to feed this small energy output. The differences in energy demand for day and night time can be seen in Figure 7-12, as well as the flow, inlet and outlet pressure of the plant for an average day in July. If the energy demand was needed to be increased during the night time, the bypass could be open and the turbine could work, thus ensuring the energy supply during the whole period. This an important advantage found when this solution was compared to solar energy, another renewable energy source that is becoming popular in irrigated farms, as the generation for this last one would be limited to daytime hours.

On the one hand, the demand is very low for the first hours of an average day in July (0 to 7am), with about 40 W consumed. At this time, the turbine is not working, as can be noticed in Figure 7-12b, since the flow is zero. An increase in the energy consumption coincides with the beginning of the working day, when the some of the farm level devices were switched on and the bypass open for the turbine to start working again. After a few hours, the consumption again dropped to almost none and kept constant in small values of around 40 W for the rest of the day. The turbine kept working to charge the batteries and recover the energy consumed during the previous night. Thus, the plant ensured the local energy demands were met at each moment, avoiding the use of diesel and leading to the benefits already explained.

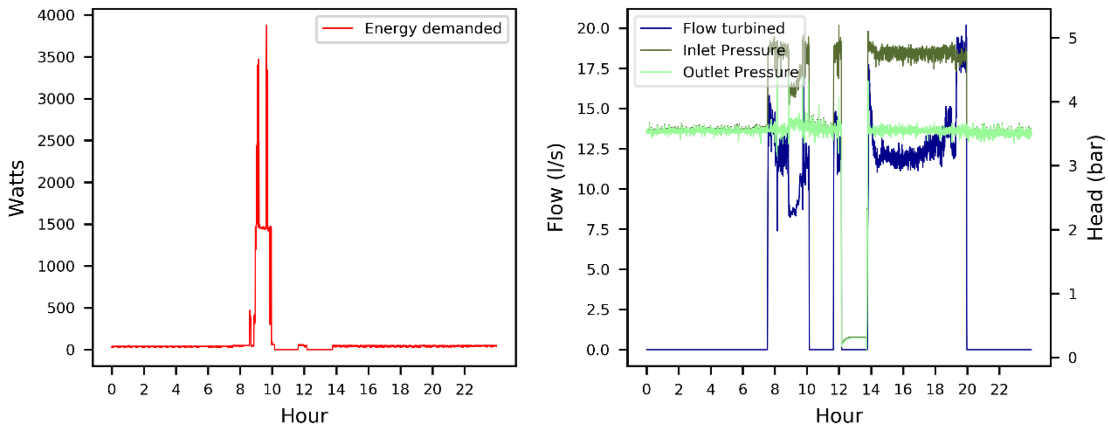

Figure 7-12. *a) Hourly power demand for an average day of July; b) Plant working variables for an average day of July.*

A seasonal evaluation of the plant global efficiency was conducted. The mean efficiency obtained was 29.5%, which is considerably lower than the 68% given as the peak efficiency of the PAT selected and the peak of 55% assumed in the design and performance estimation process. The fluctuation of the available flow and head conditions in the network has been reported in several studies as one of the main factors affecting the system efficiency for PAT installations. In low intensity irrigation periods, high head values reached the hydrant due to the low flow demands in the network. Hence, the average efficiency obtained in May and June, when the PRV was not working, oscillated around 29.5%, reaching its minimum in June, with an average efficiency of 28.3%.

The efficiency increased in July, when the PRV began operating, reaching a monthly average efficiency of 32.1%. Nevertheless, the mean value obtained for August and September decreased down to 26.5% and 26% respectively. The efficiency in these months could have increased up to design values if the PRV setting value would have been adjusted upwards. The plant efficiency variation can be seen at the top of Figure 13, while the flow diverted for such efficiencies during the whole season can be seen at the bottom in Figure 13. Overlapping both images, it could be deducted how the unstable conditions, caused by the lack of hydraulic regulation in the inlet, affected to the performance of the system. The inlet pressure is oscillating along the whole range of the head values, going from 0 (when not irrigating) to more than 7 bars (while irrigating).

From the end of June onwards, the inlet conditions were regulated as aforementioned. The analysis of the demand for the first two months indicated a very low energy consumption during most of the time (97 W on average for May and June). These high demands were concentrated in the central hours of the day, but did not reach 2 kW and lasted for only a few hours each time. Thus, when the HR was started using the upstream PRV, the inlet head was fixed to 47m, therefore allowing a maximum head drop of 12m (service head of 35m) and limiting the capacity of production of the PAT. From July forwards, it can be appreciated how the inlet head was regularised, being almost constant when the installation worked (bypass open, day time) and decreasing down to 35m (service head) when the installation was stopped but the farmer irrigated (bypass closed, night time).

It can also be noted in Figure 7-13 that there was a gap in the power production in June. This was due to a maintenance works carried out at the plant caused by a blockage of the turbine by mussels. This blockage occurred as a result during an exceptional maintenance event in the network at the filtering station of the irrigation district. Nonetheless, although the PAT was stopped the plant kept working during this period, supplying the farmer’s energy demand using the solar panels and batteries, as these requirements were low enough to be satisfied with the power produced by these in June. This would not have been the case had the blockage occurred in July or August, since the demands grew as can be seen in Figure 7-10.

The inlet head for both ER and HR can be seen in Figure 7-14 when the bypass was open in both cases. However, this was already considered in the design phase, and the batteries satisfied the demand required. Although the power production capacity was lowered by using the HR, it could be easily increased by raising up the head setting of the PRV (i.e. up to 55m, where the PAT would provoke a 20m head drop) if the farmer’s power requirements were greater. However, the mean consumption was 91 W during the whole irrigation season. Higher energy demands would have increased the global efficiency of the plant, since the PAT would work closer to the BEP for which it was designed.

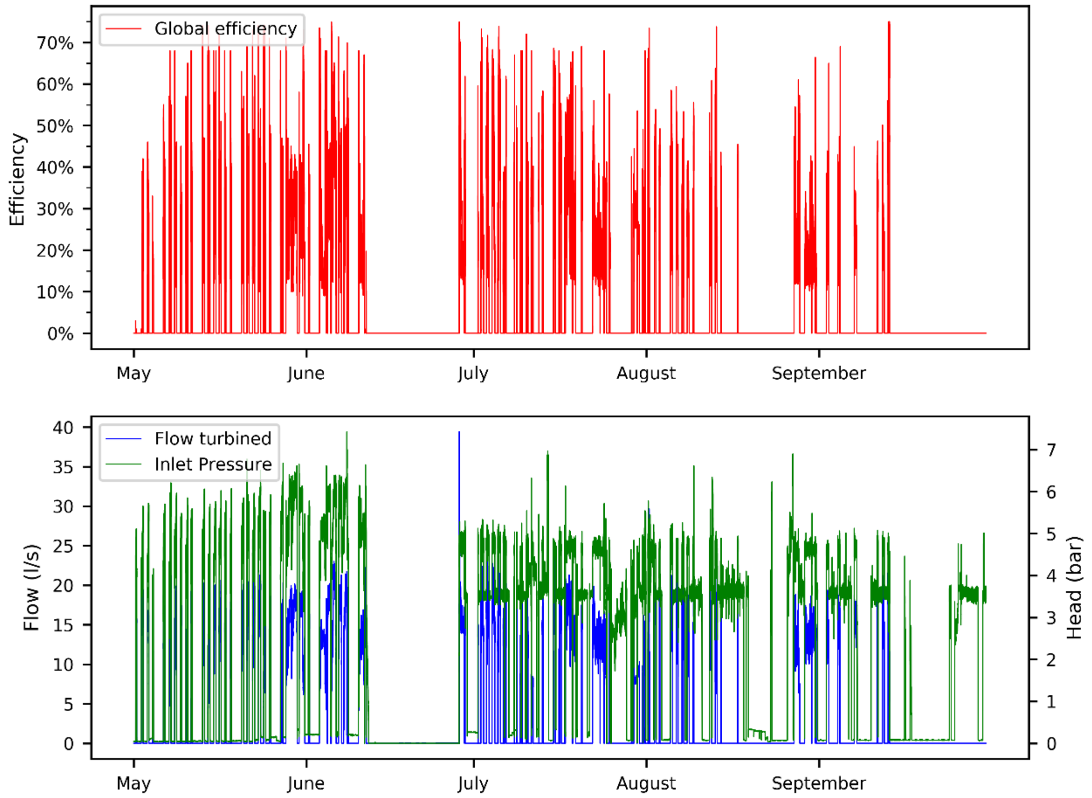

Figure 7-13. *Global plant efficiency for the data monitored during the irrigation season, depending on the flow turbined.*

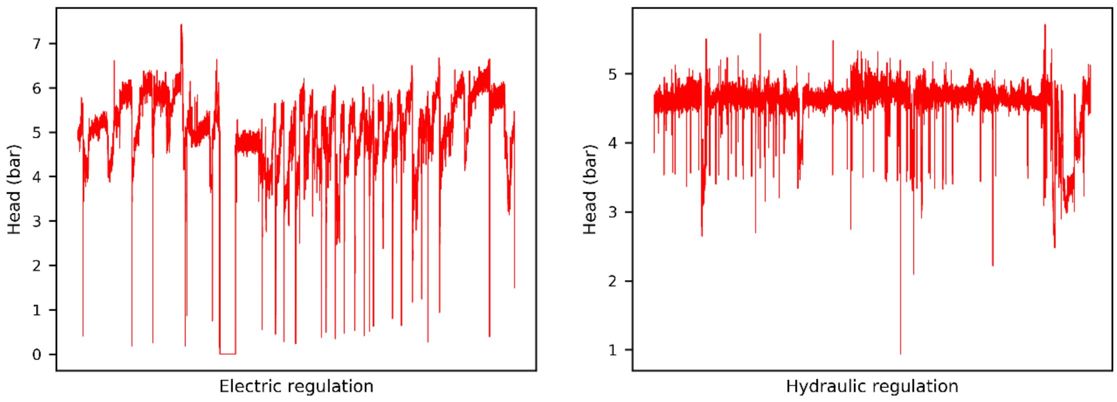

Figure 7-14. *Inlet head variations registered when ER (May and June) and HR (July to September) operated.*

Two aspects could be highlighted from this analysis. On the one hand, the low power demanded at the farm could be translated into a low global efficiency, as the plant was designed to feed the maximum energy requirements (3.6 kW). If the future demands of the farm are kept this low, it could be deduced that the plant was oversized. In order to obtain greater efficiency for such small power outputs, a smaller PAT could have been installed. Otherwise, if the energy demand increased to values closer to the maximum energy requirements considered during the design, the PAT installed would work with a global efficiency closer to the maximum. The installation of a slightly larger or smaller PAT would not greatly affect the economic performance of the plant, as the cost of the electromechanical devices would not significantly differ from one power output to other at this scale. However a smaller PAT could impact on the plant efficiency.

On the other hand, it has been shown how the stabilisation of the inlet conditions had an important role in the PAT performance. High variations of the flow and head with no hydraulic control would result in a dramatic variation of the PAT working conditions, and hence of its performance. High variations of the flow and head with only electrical regulation was also found to be insufficient to maintain a high performance. This fact could even affect to life span of the installation, as in many occasions the PAT and the generator could work under conditions much greater than specified by the manufacturer.

The theoretical approach considered 55% as the maximum efficiency, which has been demonstrated as conservative when compared to the actual maximum, 68%. Despite the fact that mean efficiency was lower, this could be increased if the demand required at farm level was greater, by setting the PRV at a higher head downstream.

Lastly, in the analysis carried out above the cost of the diesel generator was not considered in the economic analysis as it was already in existence at the pilot site. However, this may not be the case in every scenario where MHP potential exists at farm level. Considering the cost of the generator used at the farm and the diesel required annually, the payback period of the PAT to cover such investment was re-estimated. On the one hand, the total cost of the plant was reported as €22,350. On the other hand, the 2018 model of the generator used at the farm was found to have a cost of €5,151. If this capital cost was subtracted from the total cost of the PAT plant and the annual savings including April were taken into account, the payback period would decrease down to 7.1 years.

7.6. Conclusions

The existence of excess pressure in large pressurised irrigation networks has been assessed by different authors for the application of MHP energy recovery. MHP has been shown here to be an attractive solution to supply local farm-level energy demand, which is required when the farmers need to irrigate. The conditions required for MHP production are subject to large fluctuations in irrigation networks, which directly affects the energy production achievable. However, this can be partly addressed with a deep analysis of the conditions available in each case and the use of regulation and energy storage systems. The excess pressure found at the farm suffered significant fluctuations, going from almost no excess pressure to more than 50m across the season. Nevertheless, as the main aim of this MHP pilot plant was to replace a diesel generator, the energy demands could be satisfied by just taking advantage of a small amount of the head available. During the design analysis, it was seen that there was a small likelihood of no excess pressure being available during July/August, which necessitated an energy backup system.

The theoretical results predicted that the plant would be able to completely replace the diesel generator, leading to benefits in both, environmental and economical fields. 11 teCO_2 were predicted to be avoided annually and around €3,000 saved. Once the plant was constructed, the results were contrasted with the actuals performance recorded. The actual plant supplied the entire energy requirement at the farm, saving almost 3,000 litres of diesel from May to September, which offset 8.4 teCO_2 and saved over €2,250. These results increased up to 9.1 teCO_2 and more than €2,400 when the irrigation time estimated for April was considered, decreasing the payback period from 9.9 to 9.2 years.

It was also observed that HR was necessary instead of or to complement ER for high fluctuations of the PAT working conditions, as the global efficiency was affected and the life span of the plant could be reduced. Moreover, the global average efficiency obtained was significantly lower than the maximum efficiency. If the power demands kept close to the small values registered during the 2019 irrigation season, it could be deduced that the plant was oversized. On the other hand, the power installed would allow an increase of the farm's demand, as the production capacity of the plant is greater than the production required for the last campaign. This fact would allow the farmer to raise the consumption. Thus, if the demands increased to values closer to the maximum energy requirements (3.6 kW) the global efficiency of the plant would grow and the size of the plant would be justified.

Finally, fostering the adoption of sustainable solutions is an essential factor for agriculture in the short-term. Hydropower and PATs have been proven as a viable solution to satisfy the power requirements of irrigation activity at farms level, while also avoiding the use of fossil sources and all their negative impacts to the climate change. This approach gives an added value in the market to the agricultural products cultivated, which would be even bigger than the economic savings in diesel since consumers increasingly value food produced in a sustainable way. The use of diesel generators at farm level is widespread in large irrigation networks and this research presents a great opportunity to remove the impact of this activity on the environment.

7.7. Dissemination

One key point of every research is the widespread dissemination of its main findings and results in order to make them available for other researchers for their own scientific use and increase the knowledge of the scientific community of the field. Nevertheless, it is also important to bring the technology, solution or method developed and analysed in the research to the different sectors related to the research field. This would help for the real application and fostering of the solution proposed. Due to this fact, the solution proposed and studied in this thesis has been presented to different organisations related to the agriculture sector, as a potential and real technology to recover energy previously dissipated and improve the energy efficiency of water networks. This was done by means of presentations or articles, carried out during different phases of the thesis, and have been addressed to international governments, national, regional and local energy and irrigation organisations or professionals related to the issue topic among others.

Rather than the journal publications mentioned in the beginning of this thesis, the main events carried out could be divided in four, explained below:

An article about micro hydropower potential in the Spanish Technical Magazine of the Environment (RETEMA from its Spanish acronym) was published. This article dealt with the promotion of cost-effective MHP solution to be implemented in water networks in order to reduce the energy dependency of the water industry and decrease the related environmental impact. PATs were presented as a feasible solution for micro hydro generation schemes, presenting the results of some previous theoretical studies. The magazine has one of the highest technical impact in Spain and South America, and deals with the waste treatment and management, water treatment and management, and pollution. The article was published in the January/February 2019 issue.

Another article was recently published at the International Water Power and Dams Construction Magazine and at NS Energy online portal. This article was focused on the real application of MHP in water networks, highlighting three real plants encompassed within the REDAWN project. The three plants were related to different activities: one PAT was installed within a water network used by an industrial process paper factory in Portugal (RENOVA); another PAT was installed at the inlet of a water treatment plant in France; Finally, the irrigation experimental plant designed, constructed and analysed within this thesis, which was the only one operating by the time, was also explained. This article, called “Micro hydropower and the water-energy-food nexus”, was published within the November 2019 issue, available under subscription.

In addition, the plant installed in the irrigation network was also promoted and presented to public institutions, such as the Government of Tunisia or the Andalusian Energy Agency. The first presentation was held in Seville (Spain) on the 4th of April of 2019, for a delegation composed of 13 people of the different ministries of the Government of Tunisia, including Agriculture, Hydrological Resources and Fishing Ministry or the Energy Ministry. Taking into account that agriculture supposes around 15% of the GDP of Tunisia, the solution researched in this thesis (MHP and PAT) was presented to this delegation as potential solution to bring electricity to remote places with no grid connection. Two facts that could bring this solution to this country and other with similar water use climatic conditions are: i) part of Tunisia is semiarid region, where the water stress makes the need of improving the water efficiency an activity of significant importance. Furthermore, the agriculture water consumption was estimated in 80% in 2015 (Food and Agriculture Organization of the United Nations 2015). This could be translated in pressurised irrigation techniques leading to much lower water consumption; ii) and cost-effective technologies like PATs could bring electricity to remote areas with no grid connection. A picture of the event can be seen in Figure 7-15.

Finally, the PAT installation was officially launched on the 29th May 2019 during the European Energy Day organised by the REDAWN project team, celebrated in Palma del Rio (Spain), where the plant was constructed. Local farmers could be found among the people who attended to the event and their presence was highly important. Regional and local politicians were also present, as political barriers are normally found to develop this kind of projects. Researchers related to the fields of hydropower and agriculture were also present. The event was a success, with more than 50 people who attended (see Figure 7-16).

Figure 7-15. *Presentation of the PAT experimental plant to the Tunisian Government (April 2019)*

Figure 7-16. *Terry Waugh (on the left) REDAWN project leader, Professor McNabola (on the right) and Miguel Crespo (mid) presenting the experimental plant during the European Energy Day (May 2019).*

8 DISCUSSION

8.1. Introduction

This chapter summarises and discusses the main results of the thesis, as well as the potential impact on the irrigation sector, focused on the themes developed in the four previous chapters: flow fluctuations prediction and its validation, resource extrapolation and plant implementation.

8.2. Novelties of the thesis

The research carried out in this thesis was focused on the fulfilment of several targets, whose achievement has led to fill several gaps in the previous literature. The main novelties of this thesis could be summarised as follow:

1 How important flow fluctuations are for PAT design and how consideration of mean or wrong values can affect the installation economic and technical feasibility.
2 The consideration of the total combinations of open/closed hydrants is an important variable to take into account when predicting the flows, as a low number of simulations can lead to dramatic errors.
3 The average accuracy of the methodology developed in this thesis, 80%, confirmed that it could be used for flow prediction in on-demand irrigation networks and thus allowing the assessment of PATs for energy recovery.
4 The large-scale impacts of PATs, which would reduce in around 13% the energy cost in on-demand irrigation networks in Seville and Cordoba and would avoid more than 5,000 tonnes of eCO2.

5. How PATs could be used to generate electricity in remote places taking advantage of a small portion of the existing excess pressure in the network.
6. The better suitability of HR schemes for irrigation networks, where the main target is to supply the required energy rather than maximise it. With HR the working conditions of the PAT are more controlled than with ER, also with a lower cost and lower PP thus.
7. The actual effects of flow fluctuations on PAT within an irrigation network. How relative efficiency can drop and consequences of this fact on the installation performance.

8.3. Flow variation prediction and validation

The continuing upwards trend in energy consumption in the irrigation sector has led researchers to seek solutions to improve the energy efficiency. Although micro hydropower (MHP) and pumps-as-turbines (PATs) were previously analysed in these networks, some key factors must be taken into account in every evaluation: feasible flow fluctuations, variability of the turbine efficiency, operating conditions of the plant. The main aim of Chapters 4 and 5 was to develop a methodology to forecast the flow fluctuations in on-demand irrigation networks, needed to assess the MHP potential. Then, the methodology was validated comparing the results predicted with actual data from a recording system installed in an actual irrigation network. The different operating conditions were considered, as well as the variation on the turbine performance depending on the flow rate.

The seasonality of the activity makes the fluctuations very significant, passing from null flows in some stages of the year to dramatically important demands, which require the uses of very large hydraulic infrastructure (e.g. pipe diameters >1m were commonly found in networks). The method developed in Chapter 4 returned the monthly flow values, obtaining their monthly occurrence time, as well as the seasonal value. This allowed the evaluation of PATs for energy recovery.

The methodology was applied into two different on-demand irrigation networks. Firstly, in one irrigation network with no flow data, where the fluctuations were predicted and the energy recovery potential quantified. Secondly, in another network, which had a telemetry system that recorded the hourly flow. From the second case study, the comparison between actual and predicted value was carried out. The results showed a good fit, showing an average coefficient of determination (R^2) of 0.80 for the nine locations analysed. Therefore, the method was considered as reliable to predict the seasonal flow fluctuations in on-demand irrigation networks.

The results of both studies returned an energy recovery potential of 324.3 MWh in a total irrigated area of 3,611 ha. However, this potential was only found in pre-selected locations. It would be interesting to implement this into the methodology of an optimisation algorithm to obtain the optimal location of points to install turbines as well as the optimal machine to select. To do this, the flow fluctuations would need to be predicted for each pipe of the network. Thus, it would be necessary to consider every possible combination of open/closed hydrants in the network, which would require a simplification of the number of simulations in networks with high number of hydrants, since the combinations increased exponentially as per the number of hydrant. The application of optimisation algorithms for optimal locations together with PATs selection could be implemented when actual data is available, thus avoiding the computational time used for flow and head prediction.

The results of the methodology were also compared when general considerations of average flow and head or constant efficiency were used instead. These assumptions resulted in an overestimation of the power and the energy recovery potential, due to the performance of the PAT being kept constant independently on the flow rate or considering mean values. Nevertheless, previous research focused on PAT performance highlighted the importance of flow variations on the variations of PAT efficiency. Thus, it is unrealistic to consider constant efficiency, since the results obtained could show greater.

During the validation of the method, actual and predicted annual volumes consumed in the locations studied were compared. The actual irrigation volume registered was 24.9% lower than the theoretical required value. This is a common practice (deficit irrigation), and the value is within the general range registered. This deficit has come preceded by the increase of the energy consumption required in on-demand irrigation networks, which led to raise up the water costs forcing to the farmers to reduce their cost by using less water. Therefore, a dramatic increase of water costs can turn into a significant reduction of the irrigation water requirements, and thus in lower crop yields and impacts on food prices. Sustainable solutions have to be sought, which can lead to a more accessible water tariffs and no affection to farmers' productions. Incorporating MHP energy recovery in these settings could offset these operating costs and reduce deficit irrigation practices, helping to the farmers to decrease their production costs and thus the required irrigation water requirements.

The application of the method in 18 irrigation networks showed energy recovery potential all of them, founding a sum of 177 locations. The average power per location varied between 2.9 and 28.8 kW, depending on the network, with a global average of 16.9 kW. Although MHP could not supply all the energy required at irrigation districts, it is presented as an attractive and innovative solution, which takes advantage of the energy wasted in some nodes of the network. Sustainable irrigation will need the combination of different solutions, which together can decrease the energy cost to non-significant values for farmers.

One weakness of MHP application in irrigation networks would be the complexity to find points with existing potential within the irrigation sector where the energy recovered could be directly sold to the grid, stored or used for direct purposes, such as pumping. For either use, the installation costs could be importantly increased, making too many of the plants not economically attractive for investors. MHP solutions together with storage systems could be a potential way to apply the energy recovered at points where energy is required. Nevertheless, costs and logistics make this solution unviable currently for those points where no energy is needed. An attractive use for recovering energy could be at final points of the network (farm levels), where farmers with no access to electric grid tend to use diesel generators if some energy consumption is required. Adopting this alternative would reduce the amount of energy to be recovered using MHP as turbines located at farm level will inevitably have less flow and pressure available than those located higher up in the pipe network. However, this could still be considered as a potential measure to reduce the energy dependency of irrigation networks.

Comparing the energy savings obtained by MHP with other measures for improving the energy dependency in irrigation, the results obtained here showed that MHP could be an important complimentary solution. Furthermore, it could also be applied in tandem with the different energy saving measures previously highlighted in the introduction. For example, irrigation scheduling together with MHP could be a potential solution to improve energy dependency. Concerning the photovoltaic solution, this is limited for power production just during the sunlight hours. In large irrigation infrastructures, pumping using photovoltaic energy is considered as a potential solution to reduce the energy dependency. The addition of MHP to this solution in the networks could lead to an important reduction of the energy consumption in this sector.

A key endorsement of the methodology developed in Chapters 4 and 5 was its application at farm and district level in the design of the pilot plant in Chapter 7. This plant successfully replaced an on-site diesel generator with clean renewable energy for an entire irrigation season, based on the methodologies developed here. While the method has limitations due to deficit irrigation and other factors it has been shown to be a reliable basis for MHP plant design in irrigation on-demand networks.

8.4. Resource Extrapolation

The evaluation of MHP resources on a large geographical scale is important when analysing the viability of the solution proposed and the potential impacts that its application would bring at sector level. MHP and PATs have been core of many studies during the last years. However, the difficulty to obtain actual information makes the quantification of the existing resources a real challenge, which is further amplified in a large-scale geographic scope. This fact makes quite complex the estimation of the potential economic and environmental impact that would arise from the adoption of MHP quite difficult. Furthermore, as it was mentioned in Chapter 2, pumps manufacturers do not test pumps working in reverse, not providing actual PATs curves. In fact, divers methods have been developed to estimate PAT performance. Nevertheless, if large-scale assessments were developed in different water industries showing the market potential for using PATs, this could incentive pumps manufacturers to develop these curves and give precise behaviours.

A first assessment for 18 on-demand irrigation networks was done, estimating the energy recovery potential applying the methodology developed in Chapter 4. The results of this evaluation presented an interesting distribution of the potential. The two networks with the greatest potential also had the largest irrigated area, which show the strong relationship between the potential found and the irrigated surface. However, another facts influenced on the potential found in some networks. On the one hand, the elevation difference among the hydrants had impact on the pressure required at the pumping stations, increasing the pressure at many of the hydrants. On the other hand, a few undersized pipes were found at the end of some networks, increasing the pressure requirements of the issue hydrant, and thus of the entire network. It could be highlighted from this analysis that a previous analysis identifying critical points could be done prior to an energy recovery assessment using MHP.

One of the complexities of the problem approached was the relationship among the variable sought and other variables, as well as the type of relationship. Thus, Artificial Neural Networks (ANNs), which was described in Chapter 6 as powerful tool to predict variables considering no linear relationship, were used to estimate the existing energy recovery potential in on-demand irrigation networks in two regions in Andalusia (Seville and Cordoba). As samples of networks with different operating conditions (non on-demand), the method was employed in regions with similar irrigation infrastructures and design parameters for networks. The application range could be extended to areas with different type of networks, prior increasing the dataset including the network type and redefining the model (i.e. include a new proxy variable indicating the type of network, number of layers and neurons, weights, etc.).

ANNs showed a decent coefficient of determination, with a mean value of 0.63, reaching a maximum value of 0.74. The total energy recovery potential during the 2018 irrigation season raised up to 21.05 GWh. This amount was found in 180 towns located within the regions of Seville and Cordoba, areas where the irrigation is one of the most important activities, implying a significant amount of resources, personnel and economic. The assessment of the economic impact that this energy recovery would suppose to the irrigation showed a water cost decrease of €16.4 m^3, saving around 13% of the costs associated to water and energy. In addition, a significant amount of emissions would be avoided, summing more than 5 kt eCO_2 per year.

Although it is very complex and unlikely to have access to real data to carry out these kind of assessments, uncertainty must be considered in future, as this method involves non-deterministic analysis. Hence, it would be unrealistic to believe that all the energy could be either introduced to the grid or directly used at the district nowadays, due to two main reasons: lack of electric infrastructures in remote locations and increment of the cost that would turn unviable many of the installations. In the irrigation sector however, an interesting application for MHP could be the presented in Chapter 7: provide energy for self-consumption in rural farms.

8.5. Plant Implementation

Hydropower energy recovery has been proposed in literature as potential measure to reduce the energy dependency in irrigation networks. However, these studies analysed the energy dependency of the irrigation distribution network, which is the largest overall energy consumer in an irrigation district. However, these have not considered the energy requirements at farm level. Farms often require energy to carry out the irrigation activity on the farm, either for water filtering, automatic fertilisation or boosting water pressure. In addition, these farms can often be remotely located, not having access to the electric grid, and therefore necessitating the use of other sources to cover the energy demand, most commonly a diesel generator.

Due to the difficulties aforementioned about using the energy recovered, irrigation farms become alternative locations for MHP energy recovery. Two consequences have to occur at the same for such purpose: i) there must be excess pressure at the farm; ii) there must be energy consumption. If there was not excess pressure, it would not be possible to recover energy. If there was no energy consumption at the farm, there would be the same problem that in the distribution system of the irrigation network: no demand for the energy recovered.

Along this thesis, an actual scale implementation of the technology proposed was carried out. Previous investigations studied the theoretical or experimental performance of PATs installed in labs. However, no research was made of a PAT operating under actual real world irrigation network conditions. A PAT was designed to replace a diesel generator and feed the local electrical devices used during irrigation. The plant was designed to take advantage of a small amount of head from the existing excess pressure in the network and a small amount of flow from the farmer's total demand. The plant operated for over 2,400 hours in 2019, saving more than €2,200 and 8.4 t eCO_2.

Looking back to the solutions proposed in previous literature to decrease the energy dependency of irrigation networks, the adoption of one or several of these together with hydropower could suppose an important step to face the energy efficiency challenge. Comparing the energy savings obtained by MHP with other measures for improving the energy dependency in irrigation, the results obtained here showed that MHP could be an important solution. Furthermore, it could also be applied in tandem with the different energy saving measures previously highlighted in the introduction. For instance, pumping station optimtisation (first) together with MHP (secondly) could be a potential solution to improve energy dependency. Concerning the photovoltaic solution, this is limited for power production just during the sunlight hours. In large irrigation infrastructures, pumping using photovoltaic energy is considered as a potential solution to reduce the energy dependency. The addition of MHP to this solution in the networks could lead to an important reduction of the energy consumption in this sector. Coupling both technologies could be of special interest for future research.

8.6. Summary

In this chapter, the key results and findings presented in this thesis were discussed. In summary, the theoretical approach developed was able to predict the flow fluctuations during an irrigation season reliably. A coefficient of determination of 0.8 was obtained on average when the predicted values were compared to actual records. The hydropower potential estimated in large-scale returned some optimistic results for the MHP technology, but finding some barriers in the application of this energy due to lack of electric infrastructure, consumption points close to the recovery locations or cost-effective storage system. The energy recovery potential raised over 21

GWh in an irrigated area of around 160,000 ha. In addition, it was noticed that the current way to exploit the existing hydropower resources in on-demand irrigation networks could also take advantage of them at small consumption points, such as farm, where the energy could be directly used. Thus, the experimental plant was constructed at a farm that required energy during the irrigation activity. A 4 kW PAT completely replaced a diesel generator previously used, saving more than €2,200 and avoided more than 8.4 t eCO_2 for the 2019 irrigation season. The research sequence followed in this thesis provided responses to different questions within the theoretical, large-scale impact, and implementation fields: *How could an annual flow distribution be feasibly obtained? What is the large-scale impact for MHP resources in on-demand irrigation networks? Where could PATs be actually installed within on-demand irrigation networks and how would it affect single users?*

9 RESEARCH CONCLUSIONS AND FUTURE RESEARCH

9.1. Introduction

This chapter presents a summary of the key conclusions, highlights the primary contribution to knowledge and outlines any recommendations and areas requiring further research.

9.2. Contribution to knowledge

The primary contributions of this thesis were to the research and practise of hydropower energy recovery in on-demand irrigation networks. These contributions, which aimed to fulfil the targets aforementioned, included:

1. A broad gather of information and development hydraulic models related to 20 on-demand irrigation networks. This contribution led to fulfil the first target “gather information, build and calibrate hydraulic models of pressurised irrigation networks”.

2. Development of a methodology to predict the flow fluctuations and estimate the energy recovery potential selecting the theoretical PAT returning the minimum payback period in any pipe of an on-demand irrigation network. Due to the lack of actual and/or feasible flow data, which is mandatory to assess the hydropower potential, a method outputting flow fluctuation was needed. Furthermore, it seems unrealistic to consider a fix percentage over the total installation cost for civil works. Thus a cost estimation for civil

works at micro hydropower installations in irrigation networks was developed. With this methodology, targets 2 and 5 were achieved.

3. Validation of the methodology to predict the flow fluctuations comparing the results forecasted vs the actual values recorded using a telemetry system during the 2015 irrigation season in an on-demand irrigation network. With this contribution, the accuracy of the flow predictions using the method aforementioned was confirmed, fulfilling the third target set for this thesis.

4. Large-scale assessments are crucial to estimate the potential impacts of MHP on the sector and foster the technology over the PATs manufacturers and engineers working in on-demand irrigation networks. Application of linear regression models and artificial neural networks to forecast the energy recovery potential in large-scale, for an irrigated area of almost 200,000 ha, and quantification of the impacts associated to water cost and emission savings. Hence, after carrying out this analysis, the objective number four of this thesis was completed.

5. Development of the design process and construction of an actual micro hydropower plant at an irrigation farm supplied by an on-demand network, for self-consumption energy, evaluating the potential and actual impact to the farmer's economy and the environmental savings achieved. This contribution confirmed the validity of PATs to work in on-demand irrigation networks and the considerations proposed in Chapter 7 to design PAT installations could be used as guidelines for future designs and constructions. This contribution helped to fulfil targets 6, 7 and 8.

9.3. Research findings

The research carried out in this thesis resulted in numerous key findings. The first key finding was related to the variation of the energy recovery potential in on-demand irrigation networks depending on the considerations assumed. Previous investigations considered either average flow and head values or constant efficiency, which has been demonstrated that can lead to an overestimation of the power. This is mainly due to the high fluctuations suffered during the irrigation season. Thus, feasible operating values have to be used when assessing the energy recovery potential, as well as the variation of the plant performance with the operating condition variations.

Regarding the prediction of the flow fluctuations, a reliable methodology was developed to forecast them. Based on previous works, this methodology showed how important the number of simulations needed was, depending on the number of hydrants located downstream. The error on the flow values increased importantly when the number of simulations run was not enough to characterise all the open/closed hydrants combination. This fact was demonstrated when the flow predictions were compared to the actual records registered by a telemetry system installed in an on-demand irrigation network during the 2015 irrigation season. The accuracy of the predictions raised up to 80% when the steps given in the methodology developed in Chapter 4 were followed.

Linear regression models and artificial neural networks, used to consider the non-linearity, were used to estimate the annual energy recovery potential in an irrigated surface of around 160,000 ha, characterised for using on-demand irrigation networks. ANNs showed a better performance than linear models, although the complexity to define their structure was higher. The results showed how the energy efficiency could be increased if the energy could be used straight. A total potential of 21.05 GWh during 2018 for the regions of Seville and Cordoba, in Southern Spain, was predicted. Important environmental and economic benefits would be linked to this energy recovery, with more than 5,000 t eCO_2 per year and 12.8% of reduction in energy costs in irrigation. However, it was found that despite the finding energy recovery potential, generally there was no close infrastructure, to either introduce the electricity in the grid or be directly consumed.

This finding led to a change on the points where the energy recovery should be assessed: points with a local energy consumption with an existing excess pressure. Hence, the experimental plant was built at an irrigation farm. Due to the small amount of energy required at these points, just a small amount of flow and head was found to be needed at this point to satisfy the energy requirements of farmers. Therefore, the affect on the operation of the farm would be minimum. The construction of the MHP plant at an irrigation farm showed two positive impacts: i) energy would be brought to remote areas with no electricity access and where energy is required for the irrigation practice; ii) MHP could entirely substitute fossil source generators that might be used to fill in the farmer's energy requirements. Hydropower has been proven as a viable solution to satisfy the power requirements of irrigation activity at farms level, while also avoiding the use of fossil sources and all their negative impacts on air quality and climate change. This approach gives an added value in the market to the agricultural products cultivated, which would be even bigger than the economic savings in diesel since consumers increasingly value food produced in a sustainable way. The use of diesel generators at farm level is widespread in large irrigation networks and this research presents a great opportunity to remove the impact of this activity on the environment.

Another conclusion of this research thesis is related to the regulation of the working conditions of PATs in irrigation networks. Hence, HR was necessary instead of or to complement ER for high fluctuations of the PAT working conditions, as the global efficiency was affected and the life span of the plant could be reduced. Moreover, the global average efficiency obtained was significantly lower than the maximum efficiency, with an average efficiency lower than 40%. The power installed would allow an increase of the farm's demand, as the production capacity of the plant is greater than the production required for the last campaign. This fact would allow the farmer to raise the consumption. Thus, if the demands increased to values closer to the maximum energy requirements (3.6 kW) the global efficiency of the plant would grow and the size of the plant would be justified. However, a deeper analysis of the consumption pattern is required in order to adjust the energy production to the farmer´s requirement, taking into account the future possible variation of the demand, which would allow greater/lower power outputs.

Finally, it has been proved during this thesis the value of undertaking cross-disciplinary research. Though innovative methods might work theoretically, their implementation may not be viable in actual conditions. Therefore, these solutions require of the consideration of the organisations or people involved, and a clear understanding of the regulations and management of the necessary actions.

9.4. Impact of Research

This research has been disseminated in relevant in relevant water and energy platforms, both journal and conference papers, as referenced in this thesis, including:

Journal Publications

1. **M. Crespo Chacón**, J. A. Rodríguez Díaz, J. García-Morillo, and A. McNabola (2019). "Pump-as-turbine selection methodology for energy recovery in irrigation networks: Minimising the payback period," *Water (Switzerland)*, MDPI, vol. 11, no. 1, pp 1-20.

2. **M. Crespo Chacón**, J. A. Rodríguez Díaz, J. Garcia-Morillo, and A. McNabola (2020). "Hydropower energy recovery in irrigation networks: validation of a methodology for

flow prediction and pump as turbine selection," *Renewable Energy*, 147, 1728-1738.

3. **M. Crespo Chacón**, J. A. Rodríguez Díaz, J. Garcia-Morillo, and A. McNabola (2020). "Estimating regional potential for micro-hydropower energy recovery in irrigation networks on a large geographical scale," *Renewable Energy,* 155, 396-406.

4. **M. Crespo Chacón**, J. A. Rodríguez Díaz, J. Garcia-Morillo, and A. McNabola. "Evaluation of the design and long-term performance of a micro hydropower plant in a pressurised irrigation network: real world application at farm-level in Southern Spain", *Renewable Energy (Under review).*

Conference Publications

5. **M. Crespo Chacón**, J. A. Rodríguez Díaz, J. Garcia-Morillo, J. Gallagher, P. Coughlan and A. McNabola (2018). "Potential Energy Recovery Using Micro-Hydropower Technology in Irrigation Networks: Real-World Case Studies in the South of Spain." *Proceedings,* 679. 3rd International EWaS Conference: "Insights on the Water-Energy-Food Nexus", Lefkada Island, Greece 27-30 June 2018.

6. **M. Crespo Chacón**, J. A. Rodríguez Díaz, J. Garcia-Morillo, and A. McNabola (2019). "Pump-as-turbines for energy recovery: An attractive solution for auto consumption in agricultural farms". International Conference on Green Construction, 8-9 April 2019, Cordoba, Spain.

7. **M. Crespo Chacón**, J. A. Rodríguez Díaz, J. Garcia-Morillo, and A. McNabola (2020). "Evaluation of the design of a micro hydropower plant at farm level in a pressurised irrigation network in Southern Spain". 6th IAHR Europe Congress, June 30th – July 2nd, 2020, Warsaw, Poland.

The practical contribution of this research was enhanced by the collaborative nature of the REDAWN research project. The quarterly steering committee meetings and the experimental plant constructed as part of the project provided the opportunity to get valuable feedback from the key industry stakeholders and develop a unique experience on the exploitation of micro hydropower resources for self-consumption in irrigation farms or remote locations with excess pressure conditions.

9.5. Areas for future research

Developing this thesis research, various areas for future research were identified. Once the flow fluctuations can be predicted feasibly, the methodology could be implemented through optimisation algorithm to find automatically the optimal points for energy recovery. Different possibilities could be investigated, such as maximising the energy recovery or minimising the investment risk and compare the potential impacts of both strategies. This comparison could help to select the design strategy to be followed in future MHP projects in on-demand irrigation networks, depending on the existing infrastructure on each case.

Pressurised infrastructure has been shown to be water efficient while demanding an important amount of energy. On the other hand, free surface infrastructure (channels or ditches) required less energy for the water conveyance, but with a lower water efficiency. The long-term impact of the MHP is an important field to be evaluated. The importance of water and energy efficient systems and the impact of climate change on irrigation habits may change the existing hydro resources, therefore increasing or reducing the energy recovery potential. Statistical methods to assess the future climatic conditions, as well as the evolution of the cropping patterns could be useful to analyse the variation of MHP in on-demand irrigation networks.

One interesting research field would be the implementation of MHP with other solutions proposed by previous researchers (i.e. sectoring, critical points detection or renewable energy). While for solutions related to the network management, the first action to be taken should be the one reducing the energy consumption (i.e. sectoring or replace the critical points) and then identify areas with excess pressure if existed; for solutions related to other renewable energy generation, MHP and the other source(s) could be complementary, creating hybrid systems for energy supply (i.e. wind-hydro, solar-hydro).

Further research should be focused in areas related to the potential prints of MHP solutions in the irrigation sector. Thus, life cycle assessment would provide an idea of the carbon print of this technology, comparing it with other renewable energy solutions, selecting the most appropriate for each particular case. Another interesting field could evaluate how MHP would affect to food production, through reducing the costs associated to food production and increasing the added value due to green energy and the CO_2 reduction.

Finally, the research on the energy storage systems is of highly importance for the irrigation sector. The remote location of many excess pressure points makes unviable to develop plants for energy recovery. This fact makes the current potential to decrease, as much of the energy that could be recover is not technically nor economically viable. Thus, cost-effective energy storage systems could significantly increase the viable energy recovery potential.

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APPENDICES

Appendix A: Chapter 4 Further Details

A.1. Monthly mass probability values for each flow for the different EPPs

Q (l/s)	EPP 1 Mass probability function f(x)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	1.000	1.000	0.938	0.383	0.002	0.000	0.000	0.000	0.043	0.800	1.000	1.000
1	0.000	0.000	0.002	0.017	0.000	0.000	0.000	0.000	0.007	0.007	0.000	0.000
2	0.000	0.000	0.004	0.032	0.001	0.000	0.000	0.000	0.010	0.017	0.000	0.000
3	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000
4	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000
5	0.000	0.000	0.012	0.065	0.002	0.000	0.000	0.000	0.024	0.030	0.000	0.000
6	0.000	0.000	0.002	0.019	0.001	0.000	0.000	0.000	0.009	0.008	0.000	0.000
7	0.000	0.000	0.009	0.054	0.003	0.000	0.000	0.000	0.026	0.024	0.000	0.000
8	0.000	0.000	0.003	0.022	0.002	0.000	0.000	0.000	0.010	0.008	0.000	0.000
9	0.000	0.000	0.000	0.006	0.002	0.000	0.000	0.000	0.009	0.000	0.000	0.000
10	0.000	0.000	0.004	0.042	0.002	0.000	0.000	0.000	0.020	0.017	0.000	0.000
11	0.000	0.000	0.000	0.004	0.001	0.000	0.000	0.000	0.006	0.000	0.000	0.000
12	0.000	0.000	0.003	0.029	0.003	0.000	0.000	0.000	0.024	0.010	0.000	0.000
13	0.000	0.000	0.000	0.006	0.002	0.000	0.000	0.000	0.011	0.001	0.000	0.000
14	0.000	0.000	0.000	0.006	0.003	0.000	0.000	0.000	0.011	0.000	0.000	0.000
15	0.000	0.000	0.003	0.026	0.004	0.000	0.000	0.000	0.019	0.010	0.000	0.000
16	0.000	0.000	0.003	0.019	0.003	0.000	0.000	0.000	0.012	0.008	0.000	0.000
17	0.000	0.000	0.003	0.024	0.005	0.000	0.000	0.000	0.022	0.009	0.000	0.000
18	0.000	0.000	0.003	0.020	0.003	0.000	0.000	0.000	0.018	0.008	0.000	0.000
19	0.000	0.000	0.002	0.020	0.004	0.000	0.000	0.000	0.014	0.008	0.000	0.000
20	0.000	0.000	0.000	0.008	0.004	0.000	0.000	0.000	0.016	0.001	0.000	0.000
21	0.000	0.000	0.000	0.005	0.005	0.000	0.000	0.000	0.010	0.000	0.000	0.000
22	0.000	0.000	0.000	0.009	0.006	0.000	0.000	0.000	0.020	0.001	0.000	0.000
23	0.000	0.000	0.002	0.021	0.005	0.000	0.000	0.000	0.017	0.008	0.000	0.000
24	0.000	0.000	0.000	0.009	0.006	0.000	0.000	0.000	0.019	0.001	0.000	0.000
25	0.000	0.000	0.000	0.009	0.006	0.000	0.000	0.000	0.018	0.001	0.000	0.000
26	0.000	0.000	0.000	0.005	0.007	0.000	0.000	0.001	0.013	0.000	0.000	0.000
27	0.000	0.000	0.000	0.006	0.008	0.000	0.000	0.000	0.018	0.000	0.000	0.000
28	0.000	0.000	0.000	0.004	0.006	0.000	0.000	0.001	0.012	0.000	0.000	0.000
29	0.000	0.000	0.000	0.006	0.007	0.000	0.000	0.000	0.016	0.001	0.000	0.000
30	0.000	0.000	0.000	0.005	0.007	0.000	0.000	0.000	0.018	0.000	0.000	0.000
31	0.000	0.000	0.003	0.018	0.008	0.000	0.000	0.000	0.019	0.008	0.000	0.000
32	0.000	0.000	0.000	0.003	0.009	0.000	0.000	0.000	0.014	0.000	0.000	0.000
33	0.000	0.000	0.000	0.005	0.007	0.000	0.000	0.000	0.014	0.001	0.000	0.000
34	0.000	0.000	0.000	0.004	0.009	0.000	0.000	0.001	0.015	0.000	0.000	0.000
35	0.000	0.000	0.000	0.003	0.009	0.000	0.000	0.001	0.014	0.000	0.000	0.000
36	0.000	0.000	0.000	0.003	0.009	0.000	0.000	0.001	0.015	0.000	0.000	0.000
37	0.000	0.000	0.000	0.004	0.010	0.000	0.000	0.000	0.013	0.000	0.000	0.000
38	0.000	0.000	0.000	0.004	0.009	0.000	0.000	0.001	0.013	0.000	0.000	0.000
39	0.000	0.000	0.000	0.004	0.010	0.000	0.000	0.001	0.015	0.001	0.000	0.000

40	0.000	0.000	0.000	0.003	0.009	0.000	0.000	0.002	0.013	0.000	0.000	0.000
41	0.000	0.000	0.000	0.003	0.010	0.000	0.000	0.001	0.012	0.000	0.000	0.000
42	0.000	0.000	0.000	0.001	0.009	0.000	0.000	0.001	0.010	0.000	0.000	0.000
43	0.000	0.000	0.000	0.002	0.010	0.000	0.000	0.001	0.011	0.000	0.000	0.000
44	0.000	0.000	0.000	0.002	0.009	0.000	0.000	0.001	0.012	0.000	0.000	0.000
45	0.000	0.000	0.000	0.001	0.008	0.000	0.000	0.001	0.009	0.000	0.000	0.000
46	0.000	0.000	0.000	0.002	0.010	0.000	0.000	0.002	0.012	0.000	0.000	0.000
47	0.000	0.000	0.000	0.000	0.011	0.000	0.000	0.001	0.008	0.000	0.000	0.000
48	0.000	0.000	0.000	0.002	0.012	0.000	0.000	0.002	0.009	0.000	0.000	0.000
49	0.000	0.000	0.000	0.001	0.010	0.000	0.000	0.001	0.011	0.000	0.000	0.000
50	0.000	0.000	0.000	0.001	0.011	0.000	0.000	0.002	0.010	0.000	0.000	0.000
51	0.000	0.000	0.000	0.002	0.011	0.000	0.000	0.002	0.008	0.000	0.000	0.000
52	0.000	0.000	0.000	0.000	0.011	0.000	0.000	0.002	0.006	0.000	0.000	0.000
53	0.000	0.000	0.000	0.001	0.011	0.000	0.000	0.002	0.008	0.000	0.000	0.000
54	0.000	0.000	0.000	0.000	0.011	0.000	0.000	0.002	0.008	0.000	0.000	0.000
55	0.000	0.000	0.000	0.001	0.011	0.000	0.000	0.003	0.008	0.000	0.000	0.000
56	0.000	0.000	0.000	0.000	0.010	0.000	0.000	0.003	0.007	0.000	0.000	0.000
57	0.000	0.000	0.000	0.000	0.011	0.000	0.000	0.002	0.005	0.000	0.000	0.000
58	0.000	0.000	0.000	0.000	0.011	0.000	0.000	0.003	0.005	0.000	0.000	0.000
59	0.000	0.000	0.000	0.000	0.012	0.000	0.000	0.003	0.006	0.000	0.000	0.000
60	0.000	0.000	0.000	0.000	0.010	0.000	0.000	0.003	0.006	0.000	0.000	0.000
61	0.000	0.000	0.000	0.000	0.012	0.000	0.000	0.004	0.004	0.000	0.000	0.000
62	0.000	0.000	0.000	0.001	0.011	0.000	0.000	0.003	0.005	0.000	0.000	0.000
63	0.000	0.000	0.002	0.016	0.011	0.000	0.000	0.003	0.011	0.008	0.000	0.000
64	0.000	0.000	0.000	0.001	0.009	0.001	0.000	0.003	0.005	0.000	0.000	0.000
65	0.000	0.000	0.000	0.001	0.011	0.000	0.000	0.004	0.007	0.000	0.000	0.000
66	0.000	0.000	0.000	0.000	0.010	0.000	0.000	0.005	0.003	0.000	0.000	0.000
67	0.000	0.000	0.000	0.000	0.010	0.000	0.000	0.005	0.004	0.000	0.000	0.000
68	0.000	0.000	0.000	0.003	0.010	0.000	0.000	0.005	0.007	0.000	0.000	0.000
69	0.000	0.000	0.000	0.001	0.009	0.001	0.000	0.004	0.006	0.000	0.000	0.000
70	0.000	0.000	0.000	0.003	0.011	0.001	0.000	0.005	0.006	0.000	0.000	0.000
71	0.000	0.000	0.000	0.001	0.010	0.001	0.000	0.004	0.005	0.000	0.000	0.000
72	0.000	0.000	0.000	0.001	0.009	0.001	0.000	0.006	0.004	0.000	0.000	0.000
73	0.000	0.000	0.000	0.001	0.010	0.001	0.000	0.005	0.006	0.000	0.000	0.000
74	0.000	0.000	0.000	0.000	0.008	0.001	0.000	0.006	0.003	0.000	0.000	0.000
75	0.000	0.000	0.000	0.001	0.009	0.001	0.000	0.005	0.005	0.000	0.000	0.000
76	0.000	0.000	0.000	0.001	0.009	0.001	0.000	0.006	0.005	0.000	0.000	0.000
77	0.000	0.000	0.000	0.000	0.009	0.001	0.000	0.006	0.003	0.000	0.000	0.000
78	0.000	0.000	0.000	0.001	0.010	0.001	0.000	0.006	0.005	0.000	0.000	0.000
79	0.000	0.000	0.000	0.000	0.007	0.001	0.000	0.006	0.003	0.000	0.000	0.000
80	0.000	0.000	0.000	0.002	0.009	0.001	0.000	0.005	0.006	0.000	0.000	0.000
81	0.000	0.000	0.000	0.001	0.008	0.002	0.000	0.006	0.004	0.000	0.000	0.000
82	0.000	0.000	0.000	0.000	0.009	0.001	0.000	0.008	0.004	0.000	0.000	0.000
83	0.000	0.000	0.000	0.001	0.009	0.002	0.000	0.006	0.004	0.000	0.000	0.000
84	0.000	0.000	0.000	0.000	0.008	0.002	0.001	0.005	0.002	0.000	0.000	0.000
85	0.000	0.000	0.000	0.001	0.009	0.002	0.000	0.007	0.005	0.000	0.000	0.000
86	0.000	0.000	0.000	0.001	0.008	0.002	0.001	0.008	0.003	0.000	0.000	0.000
87	0.000	0.000	0.000	0.000	0.008	0.001	0.001	0.007	0.003	0.000	0.000	0.000
88	0.000	0.000	0.000	0.000	0.008	0.002	0.001	0.007	0.005	0.000	0.000	0.000
89	0.000	0.000	0.000	0.000	0.008	0.001	0.001	0.007	0.003	0.000	0.000	0.000

90	0.000	0.000	0.000	0.000	0.007	0.001	0.001	0.007	0.003	0.000	0.000	0.000
91	0.000	0.000	0.000	0.000	0.007	0.002	0.001	0.007	0.003	0.000	0.000	0.000
92	0.000	0.000	0.000	0.000	0.007	0.002	0.001	0.008	0.003	0.000	0.000	0.000
93	0.000	0.000	0.000	0.000	0.008	0.002	0.001	0.007	0.003	0.000	0.000	0.000
94	0.000	0.000	0.000	0.000	0.007	0.003	0.001	0.007	0.003	0.000	0.000	0.000
95	0.000	0.000	0.000	0.000	0.007	0.002	0.001	0.008	0.003	0.000	0.000	0.000
96	0.000	0.000	0.000	0.000	0.005	0.002	0.001	0.006	0.001	0.000	0.000	0.000
97	0.000	0.000	0.000	0.000	0.007	0.002	0.001	0.009	0.003	0.000	0.000	0.000
98	0.000	0.000	0.000	0.000	0.006	0.003	0.001	0.007	0.002	0.000	0.000	0.000
99	0.000	0.000	0.000	0.000	0.006	0.003	0.001	0.007	0.003	0.000	0.000	0.000
100	0.000	0.000	0.000	0.000	0.006	0.003	0.001	0.007	0.002	0.000	0.000	0.000
101	0.000	0.000	0.000	0.000	0.007	0.003	0.001	0.008	0.003	0.000	0.000	0.000
102	0.000	0.000	0.000	0.000	0.006	0.003	0.002	0.008	0.002	0.000	0.000	0.000
103	0.000	0.000	0.000	0.000	0.006	0.003	0.002	0.009	0.002	0.000	0.000	0.000
104	0.000	0.000	0.000	0.000	0.006	0.003	0.002	0.007	0.002	0.000	0.000	0.000
105	0.000	0.000	0.000	0.000	0.006	0.004	0.002	0.009	0.002	0.000	0.000	0.000
106	0.000	0.000	0.000	0.000	0.006	0.004	0.001	0.008	0.002	0.000	0.000	0.000
107	0.000	0.000	0.000	0.000	0.006	0.004	0.002	0.008	0.002	0.000	0.000	0.000
108	0.000	0.000	0.000	0.000	0.005	0.005	0.002	0.008	0.002	0.000	0.000	0.000
109	0.000	0.000	0.000	0.000	0.006	0.003	0.002	0.008	0.002	0.000	0.000	0.000
110	0.000	0.000	0.000	0.000	0.004	0.003	0.001	0.008	0.002	0.000	0.000	0.000
111	0.000	0.000	0.000	0.000	0.007	0.005	0.002	0.008	0.002	0.000	0.000	0.000
112	0.000	0.000	0.000	0.000	0.005	0.004	0.002	0.008	0.002	0.000	0.000	0.000
113	0.000	0.000	0.000	0.000	0.005	0.004	0.003	0.007	0.001	0.000	0.000	0.000
114	0.000	0.000	0.000	0.000	0.005	0.005	0.002	0.008	0.001	0.000	0.000	0.000
115	0.000	0.000	0.000	0.000	0.006	0.005	0.003	0.008	0.001	0.000	0.000	0.000
116	0.000	0.000	0.000	0.000	0.005	0.005	0.003	0.008	0.001	0.000	0.000	0.000
117	0.000	0.000	0.000	0.000	0.005	0.005	0.002	0.008	0.001	0.000	0.000	0.000
118	0.000	0.000	0.000	0.000	0.004	0.004	0.002	0.008	0.001	0.000	0.000	0.000
119	0.000	0.000	0.000	0.000	0.005	0.005	0.003	0.009	0.001	0.000	0.000	0.000
120	0.000	0.000	0.000	0.000	0.004	0.006	0.003	0.009	0.001	0.000	0.000	0.000
121	0.000	0.000	0.000	0.000	0.004	0.006	0.003	0.007	0.001	0.000	0.000	0.000
122	0.000	0.000	0.000	0.000	0.004	0.006	0.003	0.008	0.001	0.000	0.000	0.000
123	0.000	0.000	0.000	0.000	0.006	0.005	0.003	0.007	0.001	0.000	0.000	0.000
124	0.000	0.000	0.000	0.000	0.004	0.006	0.004	0.009	0.001	0.000	0.000	0.000
125	0.000	0.000	0.000	0.000	0.005	0.005	0.004	0.007	0.001	0.000	0.000	0.000
126	0.000	0.000	0.000	0.000	0.004	0.006	0.003	0.008	0.000	0.000	0.000	0.000
127	0.000	0.000	0.000	0.000	0.004	0.006	0.004	0.009	0.001	0.000	0.000	0.000
128	0.000	0.000	0.000	0.000	0.003	0.006	0.004	0.009	0.001	0.000	0.000	0.000
129	0.000	0.000	0.000	0.000	0.004	0.006	0.003	0.008	0.001	0.000	0.000	0.000
130	0.000	0.000	0.000	0.000	0.004	0.006	0.004	0.009	0.000	0.000	0.000	0.000
131	0.000	0.000	0.000	0.000	0.003	0.006	0.004	0.008	0.001	0.000	0.000	0.000
132	0.000	0.000	0.000	0.000	0.004	0.007	0.005	0.007	0.000	0.000	0.000	0.000
133	0.000	0.000	0.000	0.000	0.004	0.006	0.005	0.008	0.000	0.000	0.000	0.000
134	0.000	0.000	0.000	0.000	0.003	0.007	0.004	0.008	0.001	0.000	0.000	0.000
135	0.000	0.000	0.000	0.000	0.003	0.007	0.003	0.008	0.001	0.000	0.000	0.000
136	0.000	0.000	0.000	0.000	0.003	0.006	0.005	0.008	0.000	0.000	0.000	0.000
137	0.000	0.000	0.000	0.000	0.003	0.007	0.005	0.007	0.000	0.000	0.000	0.000
138	0.000	0.000	0.000	0.000	0.003	0.005	0.004	0.008	0.001	0.000	0.000	0.000
139	0.000	0.000	0.000	0.000	0.003	0.006	0.004	0.009	0.000	0.000	0.000	0.000

140	0.000	0.000	0.000	0.000	0.004	0.006	0.005	0.007	0.000	0.000	0.000	0.000
141	0.000	0.000	0.000	0.000	0.003	0.007	0.005	0.009	0.000	0.000	0.000	0.000
142	0.000	0.000	0.000	0.000	0.003	0.007	0.006	0.009	0.000	0.000	0.000	0.000
143	0.000	0.000	0.000	0.000	0.003	0.007	0.005	0.007	0.000	0.000	0.000	0.000
144	0.000	0.000	0.000	0.000	0.002	0.007	0.005	0.007	0.000	0.000	0.000	0.000
145	0.000	0.000	0.000	0.000	0.003	0.006	0.006	0.006	0.000	0.000	0.000	0.000
146	0.000	0.000	0.000	0.000	0.002	0.008	0.006	0.007	0.000	0.000	0.000	0.000
147	0.000	0.000	0.000	0.000	0.003	0.006	0.006	0.007	0.000	0.000	0.000	0.000
148	0.000	0.000	0.000	0.000	0.002	0.006	0.006	0.006	0.000	0.000	0.000	0.000
149	0.000	0.000	0.000	0.000	0.002	0.006	0.005	0.008	0.000	0.000	0.000	0.000
150	0.000	0.000	0.000	0.000	0.002	0.007	0.006	0.008	0.000	0.000	0.000	0.000
151	0.000	0.000	0.000	0.000	0.003	0.008	0.005	0.007	0.000	0.000	0.000	0.000
152	0.000	0.000	0.000	0.000	0.002	0.005	0.006	0.007	0.000	0.000	0.000	0.000
153	0.000	0.000	0.000	0.000	0.001	0.007	0.006	0.006	0.000	0.000	0.000	0.000
154	0.000	0.000	0.000	0.000	0.002	0.007	0.005	0.007	0.000	0.000	0.000	0.000
155	0.000	0.000	0.000	0.000	0.002	0.007	0.005	0.007	0.000	0.000	0.000	0.000
156	0.000	0.000	0.000	0.000	0.002	0.008	0.006	0.007	0.000	0.000	0.000	0.000
157	0.000	0.000	0.000	0.000	0.001	0.008	0.006	0.007	0.000	0.000	0.000	0.000
158	0.000	0.000	0.000	0.000	0.002	0.008	0.005	0.008	0.000	0.000	0.000	0.000
159	0.000	0.000	0.000	0.000	0.001	0.008	0.007	0.007	0.000	0.000	0.000	0.000
160	0.000	0.000	0.000	0.000	0.001	0.008	0.006	0.007	0.000	0.000	0.000	0.000
161	0.000	0.000	0.000	0.000	0.001	0.007	0.007	0.006	0.000	0.000	0.000	0.000
162	0.000	0.000	0.000	0.000	0.001	0.008	0.007	0.006	0.000	0.000	0.000	0.000
163	0.000	0.000	0.000	0.000	0.001	0.007	0.006	0.007	0.000	0.000	0.000	0.000
164	0.000	0.000	0.000	0.000	0.001	0.008	0.007	0.006	0.000	0.000	0.000	0.000
165	0.000	0.000	0.000	0.000	0.001	0.008	0.007	0.006	0.000	0.000	0.000	0.000
166	0.000	0.000	0.000	0.000	0.000	0.008	0.006	0.007	0.000	0.000	0.000	0.000
167	0.000	0.000	0.000	0.000	0.001	0.008	0.008	0.006	0.000	0.000	0.000	0.000
168	0.000	0.000	0.000	0.000	0.001	0.009	0.006	0.006	0.000	0.000	0.000	0.000
169	0.000	0.000	0.000	0.000	0.001	0.007	0.007	0.007	0.000	0.000	0.000	0.000
170	0.000	0.000	0.000	0.000	0.001	0.008	0.005	0.005	0.000	0.000	0.000	0.000
171	0.000	0.000	0.000	0.000	0.000	0.008	0.008	0.006	0.000	0.000	0.000	0.000
172	0.000	0.000	0.000	0.000	0.000	0.008	0.008	0.004	0.000	0.000	0.000	0.000
173	0.000	0.000	0.000	0.000	0.001	0.007	0.008	0.005	0.000	0.000	0.000	0.000
174	0.000	0.000	0.000	0.000	0.000	0.008	0.007	0.005	0.000	0.000	0.000	0.000
175	0.000	0.000	0.000	0.000	0.001	0.009	0.008	0.006	0.000	0.000	0.000	0.000
176	0.000	0.000	0.000	0.000	0.001	0.009	0.007	0.005	0.000	0.000	0.000	0.000
177	0.000	0.000	0.000	0.000	0.000	0.007	0.008	0.005	0.000	0.000	0.000	0.000
178	0.000	0.000	0.000	0.000	0.000	0.007	0.008	0.005	0.000	0.000	0.000	0.000
179	0.000	0.000	0.000	0.000	0.000	0.010	0.008	0.005	0.000	0.000	0.000	0.000
180	0.000	0.000	0.000	0.000	0.000	0.008	0.007	0.005	0.000	0.000	0.000	0.000
181	0.000	0.000	0.000	0.000	0.001	0.008	0.007	0.004	0.000	0.000	0.000	0.000
182	0.000	0.000	0.000	0.000	0.001	0.009	0.008	0.006	0.000	0.000	0.000	0.000
183	0.000	0.000	0.000	0.000	0.000	0.009	0.009	0.004	0.000	0.000	0.000	0.000
184	0.000	0.000	0.000	0.000	0.000	0.009	0.007	0.006	0.000	0.000	0.000	0.000
185	0.000	0.000	0.000	0.000	0.000	0.010	0.007	0.004	0.000	0.000	0.000	0.000
186	0.000	0.000	0.000	0.000	0.000	0.007	0.007	0.005	0.000	0.000	0.000	0.000
187	0.000	0.000	0.000	0.000	0.000	0.009	0.009	0.005	0.000	0.000	0.000	0.000
188	0.000	0.000	0.000	0.000	0.000	0.008	0.006	0.005	0.000	0.000	0.000	0.000
189	0.000	0.000	0.000	0.000	0.000	0.008	0.007	0.004	0.000	0.000	0.000	0.000

190	0.000	0.000	0.000	0.000	0.000	0.008	0.007	0.004	0.000	0.000	0.000	0.000
191	0.000	0.000	0.000	0.000	0.000	0.008	0.008	0.004	0.000	0.000	0.000	0.000
192	0.000	0.000	0.000	0.000	0.000	0.007	0.008	0.004	0.000	0.000	0.000	0.000
193	0.000	0.000	0.000	0.000	0.000	0.008	0.009	0.004	0.000	0.000	0.000	0.000
194	0.000	0.000	0.000	0.000	0.000	0.008	0.008	0.004	0.000	0.000	0.000	0.000
195	0.000	0.000	0.000	0.000	0.000	0.006	0.009	0.003	0.000	0.000	0.000	0.000
196	0.000	0.000	0.000	0.000	0.000	0.007	0.008	0.002	0.000	0.000	0.000	0.000
197	0.000	0.000	0.000	0.000	0.000	0.007	0.009	0.003	0.000	0.000	0.000	0.000
198	0.000	0.000	0.000	0.000	0.000	0.009	0.010	0.003	0.000	0.000	0.000	0.000
199	0.000	0.000	0.000	0.000	0.000	0.009	0.010	0.003	0.000	0.000	0.000	0.000
200	0.000	0.000	0.000	0.000	0.000	0.008	0.007	0.002	0.000	0.000	0.000	0.000
201	0.000	0.000	0.000	0.000	0.000	0.007	0.009	0.003	0.000	0.000	0.000	0.000
202	0.000	0.000	0.000	0.000	0.000	0.008	0.010	0.003	0.000	0.000	0.000	0.000
203	0.000	0.000	0.000	0.000	0.000	0.008	0.010	0.002	0.000	0.000	0.000	0.000
204	0.000	0.000	0.000	0.000	0.000	0.007	0.008	0.003	0.000	0.000	0.000	0.000
205	0.000	0.000	0.000	0.000	0.000	0.007	0.008	0.003	0.000	0.000	0.000	0.000
206	0.000	0.000	0.000	0.000	0.000	0.006	0.009	0.002	0.000	0.000	0.000	0.000
207	0.000	0.000	0.000	0.000	0.000	0.007	0.008	0.003	0.000	0.000	0.000	0.000
208	0.000	0.000	0.000	0.000	0.000	0.008	0.010	0.002	0.000	0.000	0.000	0.000
209	0.000	0.000	0.000	0.000	0.000	0.006	0.009	0.002	0.000	0.000	0.000	0.000
210	0.000	0.000	0.000	0.000	0.000	0.007	0.009	0.001	0.000	0.000	0.000	0.000
211	0.000	0.000	0.000	0.000	0.000	0.008	0.008	0.002	0.000	0.000	0.000	0.000
212	0.000	0.000	0.000	0.000	0.000	0.007	0.008	0.002	0.000	0.000	0.000	0.000
213	0.000	0.000	0.000	0.000	0.000	0.007	0.008	0.001	0.000	0.000	0.000	0.000
214	0.000	0.000	0.000	0.000	0.000	0.008	0.009	0.001	0.000	0.000	0.000	0.000
215	0.000	0.000	0.000	0.000	0.000	0.007	0.009	0.001	0.000	0.000	0.000	0.000
216	0.000	0.000	0.000	0.000	0.000	0.006	0.008	0.002	0.000	0.000	0.000	0.000
217	0.000	0.000	0.000	0.000	0.000	0.008	0.009	0.002	0.000	0.000	0.000	0.000
218	0.000	0.000	0.000	0.000	0.000	0.006	0.009	0.001	0.000	0.000	0.000	0.000
219	0.000	0.000	0.000	0.000	0.000	0.007	0.008	0.001	0.000	0.000	0.000	0.000
220	0.000	0.000	0.000	0.000	0.000	0.007	0.009	0.001	0.000	0.000	0.000	0.000
221	0.000	0.000	0.000	0.000	0.000	0.006	0.008	0.001	0.000	0.000	0.000	0.000
222	0.000	0.000	0.000	0.000	0.000	0.006	0.009	0.001	0.000	0.000	0.000	0.000
223	0.000	0.000	0.000	0.000	0.000	0.005	0.008	0.001	0.000	0.000	0.000	0.000
224	0.000	0.000	0.000	0.000	0.000	0.006	0.008	0.001	0.000	0.000	0.000	0.000
225	0.000	0.000	0.000	0.000	0.000	0.005	0.009	0.001	0.000	0.000	0.000	0.000
226	0.000	0.000	0.000	0.000	0.000	0.005	0.009	0.001	0.000	0.000	0.000	0.000
227	0.000	0.000	0.000	0.000	0.000	0.005	0.009	0.001	0.000	0.000	0.000	0.000
228	0.000	0.000	0.000	0.000	0.000	0.004	0.010	0.001	0.000	0.000	0.000	0.000
229	0.000	0.000	0.000	0.000	0.000	0.005	0.008	0.001	0.000	0.000	0.000	0.000
230	0.000	0.000	0.000	0.000	0.000	0.006	0.008	0.001	0.000	0.000	0.000	0.000
231	0.000	0.000	0.000	0.000	0.000	0.005	0.007	0.000	0.000	0.000	0.000	0.000
232	0.000	0.000	0.000	0.000	0.000	0.006	0.007	0.001	0.000	0.000	0.000	0.000
233	0.000	0.000	0.000	0.000	0.000	0.003	0.009	0.000	0.000	0.000	0.000	0.000
234	0.000	0.000	0.000	0.000	0.000	0.004	0.007	0.000	0.000	0.000	0.000	0.000
235	0.000	0.000	0.000	0.000	0.000	0.004	0.007	0.001	0.000	0.000	0.000	0.000
236	0.000	0.000	0.000	0.000	0.000	0.003	0.007	0.000	0.000	0.000	0.000	0.000
237	0.000	0.000	0.000	0.000	0.000	0.004	0.007	0.000	0.000	0.000	0.000	0.000
238	0.000	0.000	0.000	0.000	0.000	0.003	0.007	0.001	0.000	0.000	0.000	0.000
239	0.000	0.000	0.000	0.000	0.000	0.003	0.006	0.000	0.000	0.000	0.000	0.000

240	0.000	0.000	0.000	0.000	0.000	0.004	0.005	0.000	0.000	0.000	0.000	0.000
241	0.000	0.000	0.000	0.000	0.000	0.003	0.006	0.000	0.000	0.000	0.000	0.000
242	0.000	0.000	0.000	0.000	0.000	0.003	0.007	0.000	0.000	0.000	0.000	0.000
243	0.000	0.000	0.000	0.000	0.000	0.002	0.005	0.000	0.000	0.000	0.000	0.000
244	0.000	0.000	0.000	0.000	0.000	0.002	0.005	0.000	0.000	0.000	0.000	0.000
245	0.000	0.000	0.000	0.000	0.000	0.002	0.006	0.000	0.000	0.000	0.000	0.000
246	0.000	0.000	0.000	0.000	0.000	0.002	0.005	0.000	0.000	0.000	0.000	0.000
247	0.000	0.000	0.000	0.000	0.000	0.002	0.006	0.000	0.000	0.000	0.000	0.000
248	0.000	0.000	0.000	0.000	0.000	0.002	0.005	0.000	0.000	0.000	0.000	0.000
249	0.000	0.000	0.000	0.000	0.000	0.002	0.005	0.000	0.000	0.000	0.000	0.000
250	0.000	0.000	0.000	0.000	0.000	0.001	0.005	0.000	0.000	0.000	0.000	0.000
251	0.000	0.000	0.000	0.000	0.000	0.002	0.005	0.000	0.000	0.000	0.000	0.000
252	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.000	0.000	0.000	0.000	0.000
253	0.000	0.000	0.000	0.000	0.000	0.001	0.004	0.000	0.000	0.000	0.000	0.000
254	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.000	0.000	0.000	0.000	0.000
255	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.000	0.000	0.000	0.000	0.000
256	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.000	0.000	0.000	0.000	0.000
257	0.000	0.000	0.000	0.000	0.000	0.002	0.003	0.000	0.000	0.000	0.000	0.000
258	0.000	0.000	0.000	0.000	0.000	0.001	0.004	0.000	0.000	0.000	0.000	0.000
259	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.000	0.000	0.000	0.000	0.000
260	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.000	0.000	0.000	0.000	0.000
261	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.000	0.000	0.000	0.000	0.000
262	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.000	0.000	0.000	0.000	0.000
263	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.000	0.000	0.000	0.000	0.000
264	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.000	0.000	0.000	0.000	0.000
265	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.000	0.000	0.000	0.000	0.000
266	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000
267	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.000	0.000	0.000	0.000	0.000
268	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000
269	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000
270	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000
271	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000
272	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000
273	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000
274	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000
275	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000
276	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000
277	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000
278	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
279	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000
280	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
281	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000
282	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
283	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
284	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
285	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
286	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
287	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
288	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
289	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

290	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
291	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
293	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Q (l/s)	EPP 2 Mass probability function f(x)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
0	1.000	1.000	0.985	0.808	0.232	0.014	0.006	0.058	0.493	0.951	1.000	1.000
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	0.000	0.000	0.003	0.032	0.079	0.017	0.011	0.046	0.077	0.009	0.000	0.000
9	0.000	0.000	0.003	0.035	0.076	0.017	0.011	0.044	0.076	0.010	0.000	0.000
10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.001	0.027	0.024	0.018	0.032	0.011	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
19	0.000	0.000	0.003	0.035	0.079	0.019	0.011	0.042	0.075	0.010	0.000	0.000
20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
23	0.000	0.000	0.003	0.035	0.078	0.019	0.011	0.045	0.075	0.009	0.000	0.000
24	0.000	0.000	0.003	0.038	0.081	0.019	0.010	0.044	0.077	0.010	0.000	0.000
25	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
26	0.000	0.000	0.000	0.002	0.028	0.026	0.020	0.035	0.011	0.000	0.000	0.000
27	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
28	0.000	0.000	0.000	0.002	0.024	0.024	0.019	0.034	0.010	0.000	0.000	0.000
29	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.001	0.028	0.024	0.018	0.035	0.011	0.000	0.000	0.000
31	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
32	0.000	0.000	0.000	0.003	0.051	0.048	0.037	0.070	0.022	0.000	0.000	0.000
33	0.000	0.000	0.000	0.001	0.028	0.025	0.019	0.032	0.011	0.000	0.000	0.000
34	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
35	0.000	0.000	0.000	0.000	0.011	0.035	0.032	0.028	0.001	0.000	0.000	0.000
36	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
37	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
38	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
39	0.000	0.000	0.000	0.000	0.009	0.034	0.034	0.026	0.002	0.000	0.000	0.000
40	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
41	0.000	0.000	0.000	0.000	0.009	0.033	0.035	0.026	0.002	0.000	0.000	0.000
42	0.000	0.000	0.000	0.002	0.026	0.025	0.021	0.033	0.011	0.000	0.000	0.000

43	0.000	0.000	0.000	0.001	0.026	0.027	0.019	0.034	0.011	0.000	0.000	0.000
44	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
45	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
46	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
47	0.000	0.000	0.000	0.002	0.026	0.023	0.018	0.035	0.011	0.000	0.000	0.000
48	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
49	0.000	0.000	0.000	0.000	0.010	0.032	0.033	0.025	0.002	0.000	0.000	0.000
50	0.000	0.000	0.000	0.000	0.010	0.033	0.034	0.027	0.001	0.000	0.000	0.000
51	0.000	0.000	0.000	0.000	0.010	0.032	0.034	0.027	0.002	0.000	0.000	0.000
52	0.000	0.000	0.000	0.000	0.008	0.034	0.034	0.025	0.002	0.000	0.000	0.000
53	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
54	0.000	0.000	0.000	0.000	0.009	0.037	0.038	0.027	0.002	0.000	0.000	0.000
55	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
56	0.000	0.000	0.000	0.000	0.010	0.037	0.033	0.027	0.002	0.000	0.000	0.000
57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
58	0.000	0.000	0.000	0.000	0.003	0.047	0.061	0.020	0.000	0.000	0.000	0.000
59	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
60	0.000	0.000	0.000	0.000	0.003	0.049	0.062	0.021	0.000	0.000	0.000	0.000
61	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
62	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
63	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
64	0.000	0.000	0.000	0.000	0.004	0.047	0.061	0.020	0.000	0.000	0.000	0.000
65	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
66	0.000	0.000	0.000	0.000	0.010	0.035	0.033	0.027	0.001	0.000	0.000	0.000
67	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
68	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
69	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
70	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
71	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
72	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
73	0.000	0.000	0.000	0.000	0.002	0.049	0.059	0.019	0.000	0.000	0.000	0.000
74	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
75	0.000	0.000	0.000	0.000	0.003	0.049	0.060	0.020	0.000	0.000	0.000	0.000
76	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
77	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
78	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
79	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
80	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
81	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
82	0.000	0.000	0.000	0.000	0.001	0.066	0.110	0.015	0.000	0.000	0.000	0.000

Q (l/s)	**EPP 3 Mass probability function f(x)**											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
0	1.000	1.000	0.941	0.423	0.002	0.000	0.000	0.000	0.051	0.813	1.000	1.000
1	0.000	0.000	0.006	0.035	0.001	0.000	0.000	0.000	0.015	0.016	0.000	0.000
2	0.000	0.000	0.005	0.040	0.002	0.000	0.000	0.000	0.018	0.017	0.000	0.000
3	0.000	0.000	0.006	0.037	0.003	0.000	0.000	0.000	0.019	0.016	0.000	0.000
4	0.000	0.000	0.000	0.004	0.002	0.000	0.000	0.000	0.006	0.000	0.000	0.000
5	0.000	0.000	0.006	0.039	0.003	0.000	0.000	0.000	0.022	0.018	0.000	0.000

6	0.000	0.000	0.002	0.020	0.003	0.000	0.000	0.000	0.017	0.009	0.000	0.000
7	0.000	0.000	0.010	0.076	0.005	0.000	0.000	0.000	0.039	0.031	0.000	0.000
8	0.000	0.000	0.005	0.044	0.007	0.000	0.000	0.000	0.035	0.015	0.000	0.000
9	0.000	0.000	0.003	0.028	0.007	0.000	0.000	0.000	0.029	0.009	0.000	0.000
10	0.000	0.000	0.000	0.009	0.005	0.000	0.000	0.000	0.020	0.001	0.000	0.000
11	0.000	0.000	0.000	0.009	0.008	0.000	0.000	0.000	0.020	0.001	0.000	0.000
12	0.000	0.000	0.000	0.008	0.005	0.000	0.000	0.001	0.018	0.001	0.000	0.000
13	0.000	0.000	0.000	0.009	0.009	0.000	0.000	0.000	0.023	0.001	0.000	0.000
14	0.000	0.000	0.000	0.008	0.008	0.000	0.000	0.001	0.017	0.000	0.000	0.000
15	0.000	0.000	0.003	0.025	0.011	0.000	0.000	0.001	0.032	0.008	0.000	0.000
16	0.000	0.000	0.000	0.007	0.010	0.000	0.000	0.001	0.020	0.001	0.000	0.000
17	0.000	0.000	0.003	0.023	0.011	0.000	0.000	0.000	0.025	0.010	0.000	0.000
18	0.000	0.000	0.000	0.003	0.011	0.000	0.000	0.001	0.018	0.000	0.000	0.000
19	0.000	0.000	0.003	0.021	0.010	0.000	0.000	0.001	0.023	0.009	0.000	0.000
20	0.000	0.000	0.002	0.021	0.013	0.000	0.000	0.001	0.023	0.009	0.000	0.000
21	0.000	0.000	0.000	0.003	0.010	0.000	0.000	0.001	0.015	0.000	0.000	0.000
22	0.000	0.000	0.000	0.010	0.014	0.000	0.000	0.001	0.028	0.001	0.000	0.000
23	0.000	0.000	0.000	0.005	0.014	0.000	0.000	0.002	0.020	0.000	0.000	0.000
24	0.000	0.000	0.000	0.008	0.014	0.000	0.000	0.001	0.024	0.001	0.000	0.000
25	0.000	0.000	0.000	0.005	0.014	0.000	0.000	0.002	0.019	0.000	0.000	0.000
26	0.000	0.000	0.000	0.006	0.014	0.000	0.000	0.003	0.018	0.000	0.000	0.000
27	0.000	0.000	0.003	0.025	0.014	0.000	0.000	0.003	0.027	0.008	0.000	0.000
28	0.000	0.000	0.000	0.006	0.017	0.000	0.000	0.002	0.021	0.000	0.000	0.000
29	0.000	0.000	0.000	0.005	0.015	0.000	0.000	0.002	0.021	0.000	0.000	0.000
30	0.000	0.000	0.000	0.002	0.016	0.000	0.000	0.002	0.016	0.000	0.000	0.000
31	0.000	0.000	0.000	0.002	0.015	0.000	0.000	0.004	0.016	0.000	0.000	0.000
32	0.000	0.000	0.000	0.004	0.019	0.000	0.000	0.003	0.016	0.000	0.000	0.000
33	0.000	0.000	0.000	0.001	0.016	0.000	0.000	0.004	0.013	0.000	0.000	0.000
34	0.000	0.000	0.000	0.005	0.018	0.000	0.000	0.005	0.020	0.001	0.000	0.000
35	0.000	0.000	0.000	0.003	0.021	0.000	0.000	0.004	0.016	0.000	0.000	0.000
36	0.000	0.000	0.000	0.004	0.021	0.000	0.000	0.005	0.015	0.000	0.000	0.000
37	0.000	0.000	0.000	0.002	0.020	0.000	0.000	0.004	0.013	0.000	0.000	0.000
38	0.000	0.000	0.000	0.001	0.016	0.000	0.000	0.004	0.010	0.000	0.000	0.000
39	0.000	0.000	0.000	0.001	0.020	0.001	0.000	0.004	0.011	0.000	0.000	0.000
40	0.000	0.000	0.000	0.001	0.018	0.001	0.000	0.005	0.011	0.000	0.000	0.000
41	0.000	0.000	0.000	0.002	0.017	0.001	0.000	0.005	0.010	0.000	0.000	0.000
42	0.000	0.000	0.000	0.001	0.018	0.000	0.000	0.006	0.010	0.000	0.000	0.000
43	0.000	0.000	0.000	0.001	0.016	0.001	0.000	0.007	0.009	0.000	0.000	0.000
44	0.000	0.000	0.000	0.001	0.017	0.001	0.000	0.008	0.010	0.000	0.000	0.000
45	0.000	0.000	0.000	0.000	0.014	0.001	0.000	0.007	0.007	0.000	0.000	0.000
46	0.000	0.000	0.000	0.001	0.016	0.001	0.000	0.008	0.009	0.000	0.000	0.000
47	0.000	0.000	0.000	0.002	0.016	0.001	0.001	0.009	0.009	0.000	0.000	0.000
48	0.000	0.000	0.000	0.000	0.018	0.001	0.000	0.009	0.005	0.000	0.000	0.000
49	0.000	0.000	0.000	0.000	0.016	0.002	0.000	0.009	0.007	0.000	0.000	0.000
50	0.000	0.000	0.000	0.000	0.017	0.001	0.001	0.010	0.007	0.000	0.000	0.000
51	0.000	0.000	0.000	0.000	0.014	0.003	0.000	0.011	0.005	0.000	0.000	0.000
52	0.000	0.000	0.000	0.000	0.014	0.002	0.000	0.009	0.006	0.000	0.000	0.000
53	0.000	0.000	0.000	0.000	0.014	0.003	0.001	0.011	0.005	0.000	0.000	0.000
54	0.000	0.000	0.000	0.000	0.016	0.002	0.001	0.009	0.006	0.000	0.000	0.000
55	0.000	0.000	0.000	0.000	0.012	0.003	0.001	0.012	0.005	0.000	0.000	0.000

56	0.000	0.000	0.000	0.000	0.013	0.003	0.001	0.010	0.005	0.000	0.000	0.000
57	0.000	0.000	0.000	0.000	0.012	0.002	0.001	0.011	0.004	0.000	0.000	0.000
58	0.000	0.000	0.000	0.000	0.015	0.003	0.001	0.012	0.002	0.000	0.000	0.000
59	0.000	0.000	0.000	0.000	0.013	0.003	0.001	0.011	0.003	0.000	0.000	0.000
60	0.000	0.000	0.000	0.000	0.013	0.004	0.002	0.013	0.003	0.000	0.000	0.000
61	0.000	0.000	0.000	0.000	0.012	0.003	0.002	0.013	0.003	0.000	0.000	0.000
62	0.000	0.000	0.000	0.000	0.013	0.003	0.001	0.014	0.003	0.000	0.000	0.000
63	0.000	0.000	0.000	0.000	0.012	0.005	0.002	0.013	0.002	0.000	0.000	0.000
64	0.000	0.000	0.000	0.000	0.013	0.005	0.002	0.015	0.002	0.000	0.000	0.000
65	0.000	0.000	0.000	0.000	0.010	0.005	0.003	0.015	0.002	0.000	0.000	0.000
66	0.000	0.000	0.000	0.000	0.011	0.005	0.003	0.014	0.002	0.000	0.000	0.000
67	0.000	0.000	0.000	0.000	0.010	0.005	0.002	0.013	0.002	0.000	0.000	0.000
68	0.000	0.000	0.000	0.000	0.010	0.005	0.002	0.015	0.002	0.000	0.000	0.000
69	0.000	0.000	0.000	0.000	0.008	0.007	0.003	0.013	0.001	0.000	0.000	0.000
70	0.000	0.000	0.000	0.000	0.008	0.007	0.004	0.013	0.001	0.000	0.000	0.000
71	0.000	0.000	0.000	0.000	0.009	0.006	0.003	0.015	0.002	0.000	0.000	0.000
72	0.000	0.000	0.000	0.000	0.009	0.007	0.002	0.015	0.001	0.000	0.000	0.000
73	0.000	0.000	0.000	0.000	0.006	0.007	0.004	0.016	0.001	0.000	0.000	0.000
74	0.000	0.000	0.000	0.000	0.007	0.007	0.002	0.015	0.001	0.000	0.000	0.000
75	0.000	0.000	0.000	0.000	0.007	0.007	0.004	0.015	0.001	0.000	0.000	0.000
76	0.000	0.000	0.000	0.000	0.006	0.008	0.004	0.015	0.000	0.000	0.000	0.000
77	0.000	0.000	0.000	0.000	0.005	0.008	0.005	0.015	0.001	0.000	0.000	0.000
78	0.000	0.000	0.000	0.000	0.005	0.010	0.006	0.016	0.001	0.000	0.000	0.000
79	0.000	0.000	0.000	0.000	0.004	0.010	0.007	0.016	0.000	0.000	0.000	0.000
80	0.000	0.000	0.000	0.000	0.004	0.011	0.005	0.016	0.001	0.000	0.000	0.000
81	0.000	0.000	0.000	0.000	0.005	0.010	0.006	0.015	0.001	0.000	0.000	0.000
82	0.000	0.000	0.000	0.000	0.004	0.011	0.006	0.015	0.000	0.000	0.000	0.000
83	0.000	0.000	0.000	0.000	0.005	0.011	0.007	0.013	0.000	0.000	0.000	0.000
84	0.000	0.000	0.000	0.000	0.003	0.012	0.006	0.015	0.000	0.000	0.000	0.000
85	0.000	0.000	0.000	0.000	0.004	0.011	0.007	0.014	0.000	0.000	0.000	0.000
86	0.000	0.000	0.000	0.000	0.004	0.012	0.008	0.014	0.000	0.000	0.000	0.000
87	0.000	0.000	0.000	0.000	0.004	0.011	0.009	0.014	0.000	0.000	0.000	0.000
88	0.000	0.000	0.000	0.000	0.004	0.013	0.009	0.012	0.000	0.000	0.000	0.000
89	0.000	0.000	0.000	0.000	0.003	0.012	0.008	0.013	0.000	0.000	0.000	0.000
90	0.000	0.000	0.000	0.000	0.003	0.015	0.009	0.014	0.000	0.000	0.000	0.000
91	0.000	0.000	0.000	0.000	0.002	0.014	0.011	0.014	0.000	0.000	0.000	0.000
92	0.000	0.000	0.000	0.000	0.002	0.013	0.011	0.014	0.000	0.000	0.000	0.000
93	0.000	0.000	0.000	0.000	0.002	0.015	0.010	0.014	0.000	0.000	0.000	0.000
94	0.000	0.000	0.000	0.000	0.002	0.014	0.011	0.014	0.000	0.000	0.000	0.000
95	0.000	0.000	0.000	0.000	0.001	0.014	0.011	0.013	0.000	0.000	0.000	0.000
96	0.000	0.000	0.000	0.000	0.002	0.014	0.012	0.013	0.000	0.000	0.000	0.000
97	0.000	0.000	0.000	0.000	0.002	0.015	0.012	0.012	0.000	0.000	0.000	0.000
98	0.000	0.000	0.000	0.000	0.001	0.015	0.012	0.013	0.000	0.000	0.000	0.000
99	0.000	0.000	0.000	0.000	0.001	0.015	0.015	0.010	0.000	0.000	0.000	0.000
100	0.000	0.000	0.000	0.000	0.001	0.017	0.014	0.011	0.000	0.000	0.000	0.000
101	0.000	0.000	0.000	0.000	0.001	0.015	0.013	0.011	0.000	0.000	0.000	0.000
102	0.000	0.000	0.000	0.000	0.001	0.016	0.013	0.010	0.000	0.000	0.000	0.000
103	0.000	0.000	0.000	0.000	0.001	0.016	0.014	0.009	0.000	0.000	0.000	0.000
104	0.000	0.000	0.000	0.000	0.001	0.015	0.012	0.009	0.000	0.000	0.000	0.000
105	0.000	0.000	0.000	0.000	0.001	0.017	0.015	0.008	0.000	0.000	0.000	0.000

106	0.000	0.000	0.000	0.000	0.001	0.015	0.014	0.010	0.000	0.000	0.000	0.000
107	0.000	0.000	0.000	0.000	0.001	0.016	0.016	0.009	0.000	0.000	0.000	0.000
108	0.000	0.000	0.000	0.000	0.001	0.018	0.016	0.006	0.000	0.000	0.000	0.000
109	0.000	0.000	0.000	0.000	0.000	0.015	0.015	0.008	0.000	0.000	0.000	0.000
110	0.000	0.000	0.000	0.000	0.001	0.015	0.016	0.006	0.000	0.000	0.000	0.000
111	0.000	0.000	0.000	0.000	0.000	0.016	0.017	0.007	0.000	0.000	0.000	0.000
112	0.000	0.000	0.000	0.000	0.000	0.015	0.017	0.006	0.000	0.000	0.000	0.000
113	0.000	0.000	0.000	0.000	0.000	0.014	0.015	0.006	0.000	0.000	0.000	0.000
114	0.000	0.000	0.000	0.000	0.000	0.015	0.016	0.006	0.000	0.000	0.000	0.000
115	0.000	0.000	0.000	0.000	0.000	0.014	0.017	0.005	0.000	0.000	0.000	0.000
116	0.000	0.000	0.000	0.000	0.000	0.013	0.017	0.005	0.000	0.000	0.000	0.000
117	0.000	0.000	0.000	0.000	0.000	0.014	0.014	0.005	0.000	0.000	0.000	0.000
118	0.000	0.000	0.000	0.000	0.000	0.013	0.015	0.005	0.000	0.000	0.000	0.000
119	0.000	0.000	0.000	0.000	0.000	0.014	0.013	0.005	0.000	0.000	0.000	0.000
120	0.000	0.000	0.000	0.000	0.000	0.013	0.018	0.005	0.000	0.000	0.000	0.000
121	0.000	0.000	0.000	0.000	0.000	0.016	0.016	0.005	0.000	0.000	0.000	0.000
122	0.000	0.000	0.000	0.000	0.000	0.012	0.016	0.003	0.000	0.000	0.000	0.000
123	0.000	0.000	0.000	0.000	0.000	0.011	0.012	0.003	0.000	0.000	0.000	0.000
124	0.000	0.000	0.000	0.000	0.000	0.012	0.016	0.003	0.000	0.000	0.000	0.000
125	0.000	0.000	0.000	0.000	0.000	0.012	0.016	0.003	0.000	0.000	0.000	0.000
126	0.000	0.000	0.000	0.000	0.000	0.010	0.015	0.003	0.000	0.000	0.000	0.000
127	0.000	0.000	0.000	0.000	0.000	0.010	0.016	0.003	0.000	0.000	0.000	0.000
128	0.000	0.000	0.000	0.000	0.000	0.012	0.013	0.002	0.000	0.000	0.000	0.000
129	0.000	0.000	0.000	0.000	0.000	0.011	0.015	0.002	0.000	0.000	0.000	0.000
130	0.000	0.000	0.000	0.000	0.000	0.011	0.015	0.002	0.000	0.000	0.000	0.000
131	0.000	0.000	0.000	0.000	0.000	0.011	0.014	0.001	0.000	0.000	0.000	0.000
132	0.000	0.000	0.000	0.000	0.000	0.009	0.015	0.001	0.000	0.000	0.000	0.000
133	0.000	0.000	0.000	0.000	0.000	0.009	0.014	0.001	0.000	0.000	0.000	0.000
134	0.000	0.000	0.000	0.000	0.000	0.008	0.012	0.001	0.000	0.000	0.000	0.000
135	0.000	0.000	0.000	0.000	0.000	0.007	0.013	0.001	0.000	0.000	0.000	0.000
136	0.000	0.000	0.000	0.000	0.000	0.006	0.013	0.001	0.000	0.000	0.000	0.000
137	0.000	0.000	0.000	0.000	0.000	0.007	0.011	0.001	0.000	0.000	0.000	0.000
138	0.000	0.000	0.000	0.000	0.000	0.006	0.013	0.001	0.000	0.000	0.000	0.000
139	0.000	0.000	0.000	0.000	0.000	0.006	0.010	0.001	0.000	0.000	0.000	0.000
140	0.000	0.000	0.000	0.000	0.000	0.005	0.011	0.001	0.000	0.000	0.000	0.000
141	0.000	0.000	0.000	0.000	0.000	0.006	0.010	0.001	0.000	0.000	0.000	0.000
142	0.000	0.000	0.000	0.000	0.000	0.005	0.009	0.001	0.000	0.000	0.000	0.000
143	0.000	0.000	0.000	0.000	0.000	0.005	0.011	0.000	0.000	0.000	0.000	0.000
144	0.000	0.000	0.000	0.000	0.000	0.004	0.009	0.000	0.000	0.000	0.000	0.000
145	0.000	0.000	0.000	0.000	0.000	0.004	0.008	0.001	0.000	0.000	0.000	0.000
146	0.000	0.000	0.000	0.000	0.000	0.004	0.009	0.001	0.000	0.000	0.000	0.000
147	0.000	0.000	0.000	0.000	0.000	0.004	0.008	0.001	0.000	0.000	0.000	0.000
148	0.000	0.000	0.000	0.000	0.000	0.004	0.007	0.000	0.000	0.000	0.000	0.000
149	0.000	0.000	0.000	0.000	0.000	0.003	0.008	0.001	0.000	0.000	0.000	0.000
150	0.000	0.000	0.000	0.000	0.000	0.004	0.007	0.000	0.000	0.000	0.000	0.000
151	0.000	0.000	0.000	0.000	0.000	0.003	0.005	0.000	0.000	0.000	0.000	0.000
152	0.000	0.000	0.000	0.000	0.000	0.003	0.006	0.000	0.000	0.000	0.000	0.000
153	0.000	0.000	0.000	0.000	0.000	0.002	0.004	0.000	0.000	0.000	0.000	0.000
154	0.000	0.000	0.000	0.000	0.000	0.002	0.005	0.000	0.000	0.000	0.000	0.000
155	0.000	0.000	0.000	0.000	0.000	0.002	0.004	0.000	0.000	0.000	0.000	0.000

156	0.000	0.000	0.000	0.000	0.000	0.002	0.004	0.000	0.000	0.000	0.000	0.000
157	0.000	0.000	0.000	0.000	0.000	0.001	0.004	0.000	0.000	0.000	0.000	0.000
158	0.000	0.000	0.000	0.000	0.000	0.002	0.003	0.000	0.000	0.000	0.000	0.000
159	0.000	0.000	0.000	0.000	0.000	0.001	0.004	0.000	0.000	0.000	0.000	0.000
160	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.000	0.000	0.000	0.000	0.000
161	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.000	0.000	0.000	0.000	0.000
162	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.000	0.000	0.000	0.000	0.000
163	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.000	0.000	0.000	0.000	0.000
164	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000
165	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.000	0.000	0.000	0.000	0.000
166	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000
167	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000
168	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000
169	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000
170	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000
171	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000
172	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000
173	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
174	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
175	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
176	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
177	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
178	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
179	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Q (l/s)	**EPP 4 Mass probability function f(x)**											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
0	1.000	1.000	0.930	0.341	0.001	0.000	0.000	0.000	0.026	0.787	1.000	1.000
1	0.000	0.000	0.016	0.092	0.001	0.000	0.000	0.000	0.023	0.043	0.000	0.000
2	0.000	0.000	0.016	0.100	0.003	0.000	0.000	0.000	0.037	0.044	0.000	0.000
3	0.000	0.000	0.014	0.092	0.004	0.000	0.000	0.000	0.046	0.040	0.000	0.000
4	0.000	0.000	0.003	0.045	0.005	0.000	0.000	0.000	0.043	0.011	0.000	0.000
5	0.000	0.000	0.005	0.053	0.007	0.000	0.000	0.000	0.049	0.016	0.000	0.000
6	0.000	0.000	0.007	0.063	0.008	0.000	0.000	0.000	0.051	0.023	0.000	0.000
7	0.000	0.000	0.000	0.026	0.010	0.000	0.000	0.000	0.044	0.003	0.000	0.000
8	0.000	0.000	0.002	0.037	0.016	0.000	0.000	0.000	0.053	0.009	0.000	0.000
9	0.000	0.000	0.002	0.038	0.016	0.000	0.000	0.001	0.054	0.010	0.000	0.000
10	0.000	0.000	0.000	0.016	0.023	0.000	0.000	0.001	0.049	0.001	0.000	0.000
11	0.000	0.000	0.000	0.016	0.023	0.000	0.000	0.001	0.048	0.001	0.000	0.000
12	0.000	0.000	0.000	0.011	0.026	0.000	0.000	0.002	0.044	0.001	0.000	0.000
13	0.000	0.000	0.000	0.006	0.028	0.000	0.000	0.002	0.040	0.000	0.000	0.000
14	0.000	0.000	0.000	0.007	0.029	0.000	0.000	0.002	0.038	0.000	0.000	0.000
15	0.000	0.000	0.000	0.005	0.031	0.000	0.000	0.003	0.035	0.000	0.000	0.000
16	0.000	0.000	0.000	0.002	0.036	0.000	0.000	0.004	0.029	0.000	0.000	0.000
17	0.000	0.000	0.000	0.004	0.033	0.000	0.000	0.004	0.029	0.000	0.000	0.000
18	0.000	0.000	0.000	0.002	0.034	0.000	0.000	0.006	0.024	0.000	0.000	0.000
19	0.000	0.000	0.000	0.001	0.033	0.000	0.000	0.007	0.018	0.000	0.000	0.000
20	0.000	0.000	0.000	0.001	0.033	0.000	0.000	0.009	0.016	0.000	0.000	0.000
21	0.000	0.000	0.002	0.014	0.034	0.001	0.000	0.009	0.018	0.008	0.000	0.000

22	0.000	0.000	0.000	0.005	0.034	0.000	0.000	0.010	0.016	0.000	0.000	0.000
23	0.000	0.000	0.000	0.004	0.030	0.001	0.000	0.013	0.015	0.000	0.000	0.000
24	0.000	0.000	0.000	0.002	0.029	0.002	0.000	0.014	0.012	0.000	0.000	0.000
25	0.000	0.000	0.000	0.002	0.028	0.001	0.000	0.013	0.012	0.000	0.000	0.000
26	0.000	0.000	0.000	0.002	0.026	0.002	0.000	0.017	0.013	0.000	0.000	0.000
27	0.000	0.000	0.000	0.003	0.027	0.002	0.001	0.017	0.015	0.000	0.000	0.000
28	0.000	0.000	0.000	0.001	0.023	0.003	0.001	0.021	0.011	0.000	0.000	0.000
29	0.000	0.000	0.000	0.002	0.024	0.004	0.001	0.020	0.011	0.000	0.000	0.000
30	0.000	0.000	0.000	0.002	0.025	0.005	0.001	0.021	0.010	0.000	0.000	0.000
31	0.000	0.000	0.000	0.001	0.021	0.006	0.001	0.020	0.009	0.000	0.000	0.000
32	0.000	0.000	0.000	0.001	0.022	0.007	0.002	0.025	0.009	0.000	0.000	0.000
33	0.000	0.000	0.000	0.001	0.020	0.007	0.003	0.025	0.007	0.000	0.000	0.000
34	0.000	0.000	0.000	0.000	0.021	0.008	0.002	0.024	0.007	0.000	0.000	0.000
35	0.000	0.000	0.000	0.001	0.018	0.007	0.003	0.024	0.007	0.000	0.000	0.000
36	0.000	0.000	0.000	0.000	0.017	0.010	0.005	0.024	0.005	0.000	0.000	0.000
37	0.000	0.000	0.000	0.000	0.016	0.011	0.005	0.023	0.005	0.000	0.000	0.000
38	0.000	0.000	0.000	0.000	0.018	0.011	0.006	0.026	0.004	0.000	0.000	0.000
39	0.000	0.000	0.000	0.000	0.016	0.015	0.007	0.026	0.003	0.000	0.000	0.000
40	0.000	0.000	0.000	0.000	0.016	0.015	0.007	0.025	0.003	0.000	0.000	0.000
41	0.000	0.000	0.000	0.000	0.014	0.015	0.009	0.025	0.003	0.000	0.000	0.000
42	0.000	0.000	0.000	0.000	0.012	0.016	0.007	0.025	0.002	0.000	0.000	0.000
43	0.000	0.000	0.000	0.000	0.013	0.014	0.010	0.023	0.002	0.000	0.000	0.000
44	0.000	0.000	0.000	0.000	0.011	0.017	0.011	0.024	0.002	0.000	0.000	0.000
45	0.000	0.000	0.000	0.000	0.009	0.020	0.013	0.022	0.001	0.000	0.000	0.000
46	0.000	0.000	0.000	0.000	0.010	0.018	0.014	0.024	0.001	0.000	0.000	0.000
47	0.000	0.000	0.000	0.000	0.009	0.019	0.015	0.022	0.001	0.000	0.000	0.000
48	0.000	0.000	0.000	0.000	0.009	0.019	0.016	0.021	0.001	0.000	0.000	0.000
49	0.000	0.000	0.000	0.000	0.007	0.022	0.016	0.023	0.000	0.000	0.000	0.000
50	0.000	0.000	0.000	0.000	0.007	0.022	0.015	0.024	0.000	0.000	0.000	0.000
51	0.000	0.000	0.000	0.000	0.005	0.022	0.016	0.021	0.000	0.000	0.000	0.000
52	0.000	0.000	0.000	0.000	0.005	0.024	0.017	0.022	0.000	0.000	0.000	0.000
53	0.000	0.000	0.000	0.000	0.004	0.021	0.018	0.021	0.000	0.000	0.000	0.000
54	0.000	0.000	0.000	0.000	0.004	0.026	0.019	0.019	0.000	0.000	0.000	0.000
55	0.000	0.000	0.000	0.000	0.003	0.023	0.019	0.021	0.000	0.000	0.000	0.000
56	0.000	0.000	0.000	0.000	0.003	0.023	0.022	0.019	0.000	0.000	0.000	0.000
57	0.000	0.000	0.000	0.000	0.002	0.025	0.020	0.017	0.000	0.000	0.000	0.000
58	0.000	0.000	0.000	0.000	0.002	0.023	0.023	0.019	0.000	0.000	0.000	0.000
59	0.000	0.000	0.000	0.000	0.001	0.024	0.021	0.017	0.000	0.000	0.000	0.000
60	0.000	0.000	0.000	0.000	0.001	0.024	0.023	0.016	0.000	0.000	0.000	0.000
61	0.000	0.000	0.000	0.000	0.001	0.023	0.020	0.016	0.000	0.000	0.000	0.000
62	0.000	0.000	0.000	0.000	0.000	0.025	0.024	0.013	0.000	0.000	0.000	0.000
63	0.000	0.000	0.000	0.000	0.001	0.026	0.023	0.013	0.000	0.000	0.000	0.000
64	0.000	0.000	0.000	0.000	0.001	0.025	0.024	0.012	0.000	0.000	0.000	0.000
65	0.000	0.000	0.000	0.000	0.000	0.028	0.025	0.010	0.000	0.000	0.000	0.000
66	0.000	0.000	0.000	0.000	0.000	0.023	0.027	0.011	0.000	0.000	0.000	0.000
67	0.000	0.000	0.000	0.000	0.000	0.024	0.026	0.010	0.000	0.000	0.000	0.000
68	0.000	0.000	0.000	0.000	0.000	0.026	0.025	0.008	0.000	0.000	0.000	0.000
69	0.000	0.000	0.000	0.000	0.000	0.023	0.026	0.009	0.000	0.000	0.000	0.000
70	0.000	0.000	0.000	0.000	0.000	0.021	0.028	0.006	0.000	0.000	0.000	0.000
71	0.000	0.000	0.000	0.000	0.000	0.022	0.025	0.004	0.000	0.000	0.000	0.000

72	0.000	0.000	0.000	0.000	0.000	0.022	0.028	0.005	0.000	0.000	0.000	0.000
73	0.000	0.000	0.000	0.000	0.000	0.018	0.026	0.004	0.000	0.000	0.000	0.000
74	0.000	0.000	0.000	0.000	0.000	0.020	0.026	0.003	0.000	0.000	0.000	0.000
75	0.000	0.000	0.000	0.000	0.000	0.019	0.028	0.002	0.000	0.000	0.000	0.000
76	0.000	0.000	0.000	0.000	0.000	0.016	0.025	0.002	0.000	0.000	0.000	0.000
77	0.000	0.000	0.000	0.000	0.000	0.014	0.024	0.002	0.000	0.000	0.000	0.000
78	0.000	0.000	0.000	0.000	0.000	0.014	0.027	0.001	0.000	0.000	0.000	0.000
79	0.000	0.000	0.000	0.000	0.000	0.012	0.024	0.001	0.000	0.000	0.000	0.000
80	0.000	0.000	0.000	0.000	0.000	0.011	0.020	0.001	0.000	0.000	0.000	0.000
81	0.000	0.000	0.000	0.000	0.000	0.010	0.020	0.001	0.000	0.000	0.000	0.000
82	0.000	0.000	0.000	0.000	0.000	0.008	0.018	0.001	0.000	0.000	0.000	0.000
83	0.000	0.000	0.000	0.000	0.000	0.006	0.015	0.000	0.000	0.000	0.000	0.000
84	0.000	0.000	0.000	0.000	0.000	0.007	0.014	0.000	0.000	0.000	0.000	0.000
85	0.000	0.000	0.000	0.000	0.000	0.004	0.013	0.000	0.000	0.000	0.000	0.000
86	0.000	0.000	0.000	0.000	0.000	0.004	0.011	0.000	0.000	0.000	0.000	0.000
87	0.000	0.000	0.000	0.000	0.000	0.003	0.010	0.000	0.000	0.000	0.000	0.000
88	0.000	0.000	0.000	0.000	0.000	0.003	0.007	0.000	0.000	0.000	0.000	0.000
89	0.000	0.000	0.000	0.000	0.000	0.002	0.005	0.000	0.000	0.000	0.000	0.000
90	0.000	0.000	0.000	0.000	0.000	0.002	0.004	0.000	0.000	0.000	0.000	0.000
91	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.000	0.000	0.000	0.000	0.000
92	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.000	0.000	0.000
93	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000
94	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000
95	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000
96	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000
97	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
98	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
99	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Q (l/s)	**EPP 5 Mass probability function f(x)**											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
0	1.000	1.000	0.948	0.437	0.003	0.000	0.000	0.000	0.061	0.826	1.000	1.000
1	0.000	0.000	0.010	0.076	0.006	0.000	0.000	0.000	0.042	0.031	0.000	0.000
2	0.000	0.000	0.008	0.062	0.006	0.000	0.000	0.000	0.038	0.024	0.000	0.000
3	0.000	0.000	0.008	0.070	0.007	0.000	0.000	0.000	0.049	0.024	0.000	0.000
4	0.000	0.000	0.005	0.049	0.010	0.000	0.000	0.000	0.042	0.017	0.000	0.000
5	0.000	0.000	0.007	0.065	0.014	0.000	0.000	0.000	0.055	0.026	0.000	0.000
6	0.000	0.000	0.002	0.038	0.016	0.000	0.000	0.000	0.050	0.009	0.000	0.000
7	0.000	0.000	0.011	0.092	0.024	0.000	0.000	0.001	0.085	0.034	0.000	0.000
8	0.000	0.000	0.000	0.025	0.024	0.000	0.000	0.001	0.058	0.002	0.000	0.000
9	0.000	0.000	0.000	0.018	0.025	0.000	0.000	0.002	0.049	0.002	0.000	0.000
10	0.000	0.000	0.000	0.017	0.032	0.000	0.000	0.003	0.059	0.002	0.000	0.000
11	0.000	0.000	0.000	0.010	0.033	0.000	0.000	0.004	0.051	0.001	0.000	0.000
12	0.000	0.000	0.000	0.014	0.038	0.000	0.000	0.006	0.052	0.001	0.000	0.000
13	0.000	0.000	0.000	0.006	0.039	0.000	0.000	0.005	0.041	0.000	0.000	0.000
14	0.000	0.000	0.000	0.009	0.045	0.001	0.000	0.007	0.046	0.001	0.000	0.000
15	0.000	0.000	0.000	0.005	0.044	0.001	0.000	0.008	0.035	0.000	0.000	0.000
16	0.000	0.000	0.000	0.003	0.045	0.001	0.000	0.011	0.029	0.000	0.000	0.000
17	0.000	0.000	0.000	0.002	0.045	0.001	0.000	0.014	0.024	0.000	0.000	0.000

18	0.000	0.000	0.000	0.001	0.042	0.001	0.000	0.016	0.025	0.000	0.000	0.000
19	0.000	0.000	0.000	0.001	0.044	0.002	0.001	0.015	0.022	0.000	0.000	0.000
20	0.000	0.000	0.000	0.001	0.044	0.002	0.001	0.018	0.017	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000	0.042	0.004	0.002	0.022	0.015	0.000	0.000	0.000
22	0.000	0.000	0.000	0.001	0.041	0.004	0.001	0.027	0.012	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000	0.036	0.006	0.001	0.024	0.009	0.000	0.000	0.000
24	0.000	0.000	0.000	0.000	0.037	0.006	0.002	0.028	0.009	0.000	0.000	0.000
25	0.000	0.000	0.000	0.000	0.034	0.008	0.002	0.029	0.007	0.000	0.000	0.000
26	0.000	0.000	0.000	0.000	0.031	0.009	0.003	0.035	0.005	0.000	0.000	0.000
27	0.000	0.000	0.000	0.000	0.027	0.011	0.004	0.035	0.004	0.000	0.000	0.000
28	0.000	0.000	0.000	0.000	0.026	0.011	0.007	0.037	0.004	0.000	0.000	0.000
29	0.000	0.000	0.000	0.000	0.021	0.012	0.006	0.036	0.002	0.000	0.000	0.000
30	0.000	0.000	0.000	0.000	0.019	0.017	0.007	0.039	0.001	0.000	0.000	0.000
31	0.000	0.000	0.000	0.000	0.018	0.018	0.009	0.040	0.001	0.000	0.000	0.000
32	0.000	0.000	0.000	0.000	0.017	0.020	0.010	0.042	0.001	0.000	0.000	0.000
33	0.000	0.000	0.000	0.000	0.012	0.022	0.012	0.041	0.001	0.000	0.000	0.000
34	0.000	0.000	0.000	0.000	0.011	0.023	0.014	0.038	0.000	0.000	0.000	0.000
35	0.000	0.000	0.000	0.000	0.009	0.029	0.016	0.038	0.001	0.000	0.000	0.000
36	0.000	0.000	0.000	0.000	0.006	0.027	0.020	0.038	0.000	0.000	0.000	0.000
37	0.000	0.000	0.000	0.000	0.005	0.033	0.021	0.036	0.000	0.000	0.000	0.000
38	0.000	0.000	0.000	0.000	0.006	0.034	0.023	0.034	0.000	0.000	0.000	0.000
39	0.000	0.000	0.000	0.000	0.004	0.036	0.026	0.031	0.000	0.000	0.000	0.000
40	0.000	0.000	0.000	0.000	0.004	0.036	0.028	0.029	0.000	0.000	0.000	0.000
41	0.000	0.000	0.000	0.000	0.003	0.040	0.031	0.025	0.000	0.000	0.000	0.000
42	0.000	0.000	0.000	0.000	0.002	0.042	0.032	0.025	0.000	0.000	0.000	0.000
43	0.000	0.000	0.000	0.000	0.001	0.041	0.033	0.023	0.000	0.000	0.000	0.000
44	0.000	0.000	0.000	0.000	0.001	0.038	0.035	0.021	0.000	0.000	0.000	0.000
45	0.000	0.000	0.000	0.000	0.001	0.038	0.036	0.019	0.000	0.000	0.000	0.000
46	0.000	0.000	0.000	0.000	0.001	0.038	0.037	0.015	0.000	0.000	0.000	0.000
47	0.000	0.000	0.000	0.000	0.000	0.039	0.041	0.014	0.000	0.000	0.000	0.000
48	0.000	0.000	0.000	0.000	0.000	0.039	0.041	0.012	0.000	0.000	0.000	0.000
49	0.000	0.000	0.000	0.000	0.000	0.035	0.040	0.010	0.000	0.000	0.000	0.000
50	0.000	0.000	0.000	0.000	0.000	0.036	0.041	0.008	0.000	0.000	0.000	0.000
51	0.000	0.000	0.000	0.000	0.000	0.031	0.041	0.007	0.000	0.000	0.000	0.000
52	0.000	0.000	0.000	0.000	0.000	0.028	0.038	0.007	0.000	0.000	0.000	0.000
53	0.000	0.000	0.000	0.000	0.000	0.025	0.038	0.005	0.000	0.000	0.000	0.000
54	0.000	0.000	0.000	0.000	0.000	0.024	0.038	0.004	0.000	0.000	0.000	0.000
55	0.000	0.000	0.000	0.000	0.000	0.020	0.036	0.003	0.000	0.000	0.000	0.000
56	0.000	0.000	0.000	0.000	0.000	0.019	0.030	0.002	0.000	0.000	0.000	0.000
57	0.000	0.000	0.000	0.000	0.000	0.018	0.030	0.003	0.000	0.000	0.000	0.000
58	0.000	0.000	0.000	0.000	0.000	0.013	0.029	0.001	0.000	0.000	0.000	0.000
59	0.000	0.000	0.000	0.000	0.000	0.012	0.025	0.001	0.000	0.000	0.000	0.000
60	0.000	0.000	0.000	0.000	0.000	0.010	0.021	0.001	0.000	0.000	0.000	0.000
61	0.000	0.000	0.000	0.000	0.000	0.009	0.018	0.001	0.000	0.000	0.000	0.000
62	0.000	0.000	0.000	0.000	0.000	0.006	0.015	0.000	0.000	0.000	0.000	0.000
63	0.000	0.000	0.000	0.000	0.000	0.005	0.013	0.000	0.000	0.000	0.000	0.000
64	0.000	0.000	0.000	0.000	0.000	0.005	0.010	0.000	0.000	0.000	0.000	0.000
65	0.000	0.000	0.000	0.000	0.000	0.003	0.011	0.000	0.000	0.000	0.000	0.000
66	0.000	0.000	0.000	0.000	0.000	0.002	0.006	0.000	0.000	0.000	0.000	0.000
67	0.000	0.000	0.000	0.000	0.000	0.002	0.005	0.000	0.000	0.000	0.000	0.000

68	0.000	0.000	0.000	0.000	0.000	0.001	0.004	0.000	0.000	0.000	0.000	0.000
69	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.000	0.000	0.000	0.000	0.000
70	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.000	0.000	0.000	0.000	0.000
71	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000
72	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000
73	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000
74	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
75	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

A.2. Monthly binomial distributions Figures.

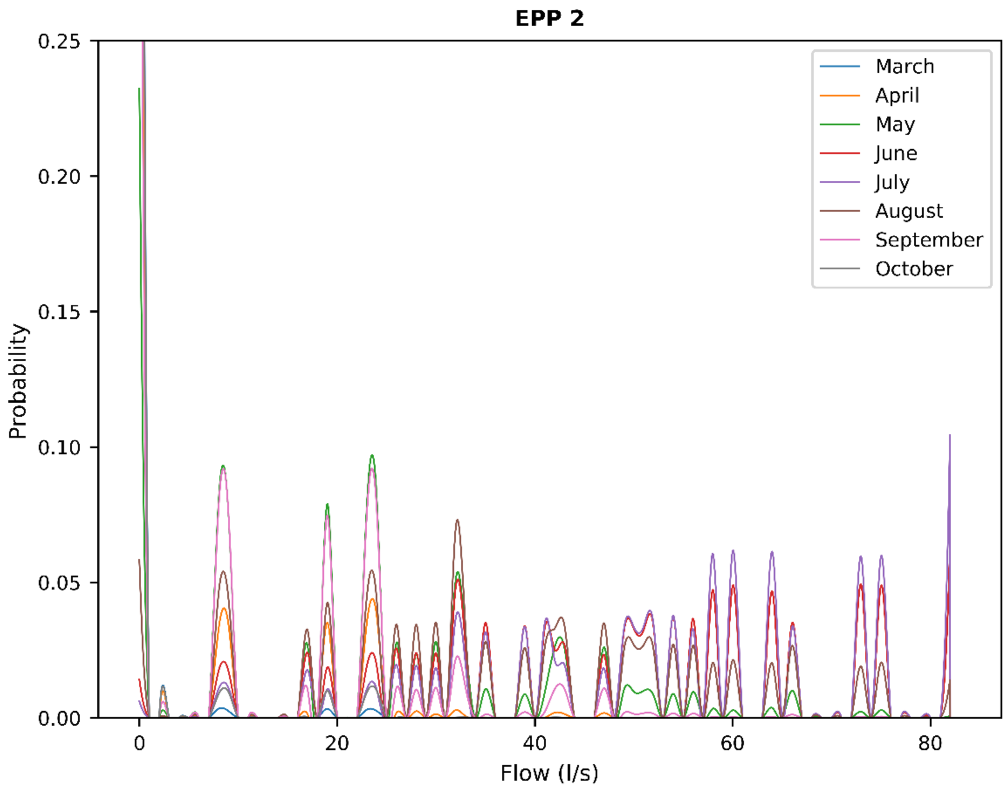

Figure A.2-1. *Monthly binomial distributions for the irrigation season for the EPP2*

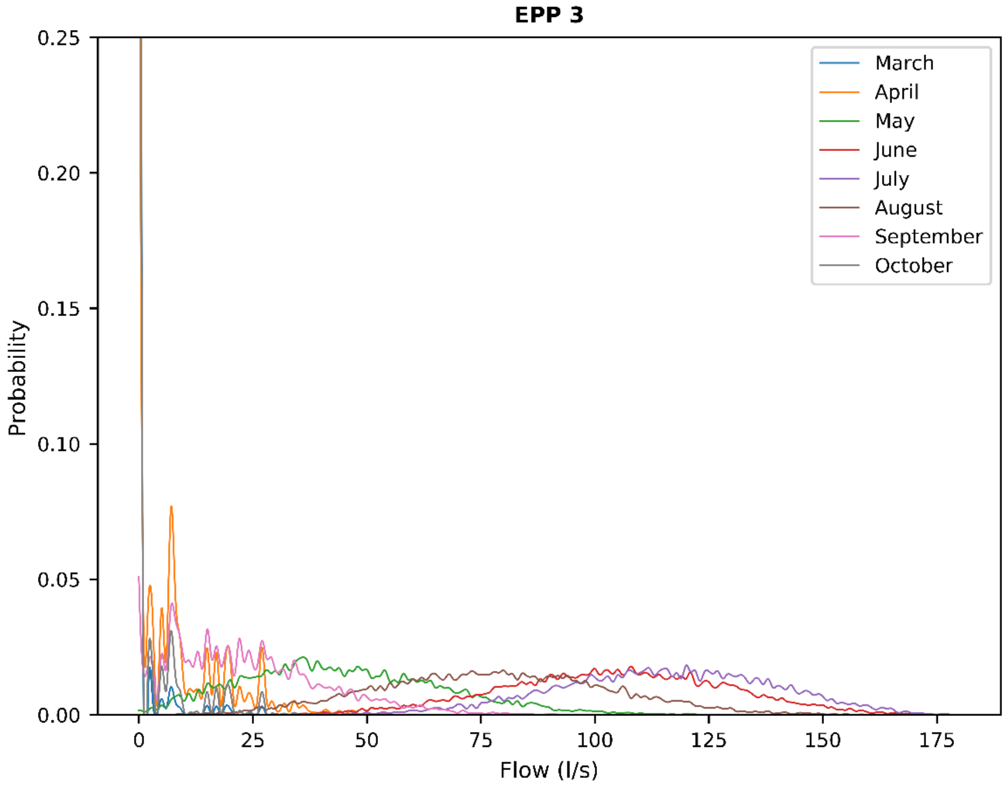

Figure A.2-2. *Monthly binomial distributions for the irrigation season for the EPP 3*

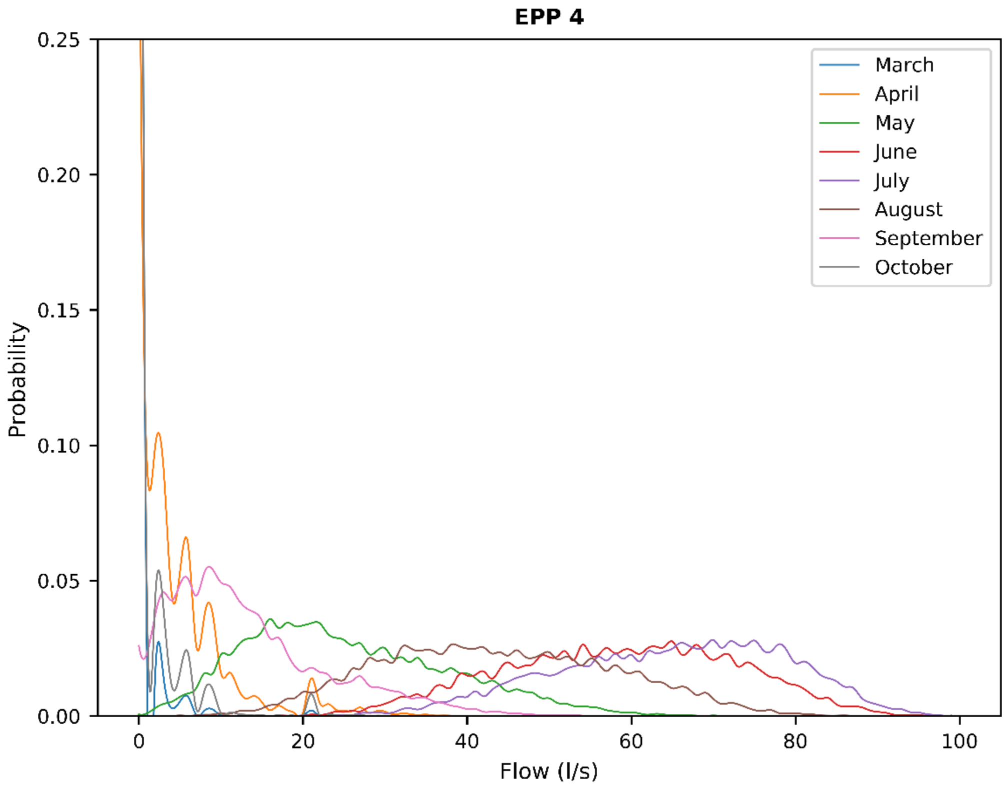

Figure A.2-3. *Monthly binomial distributions for the irrigation season for the EPP 4*

A.3. Monthly theoretical and predicted irrigation crop requirements.

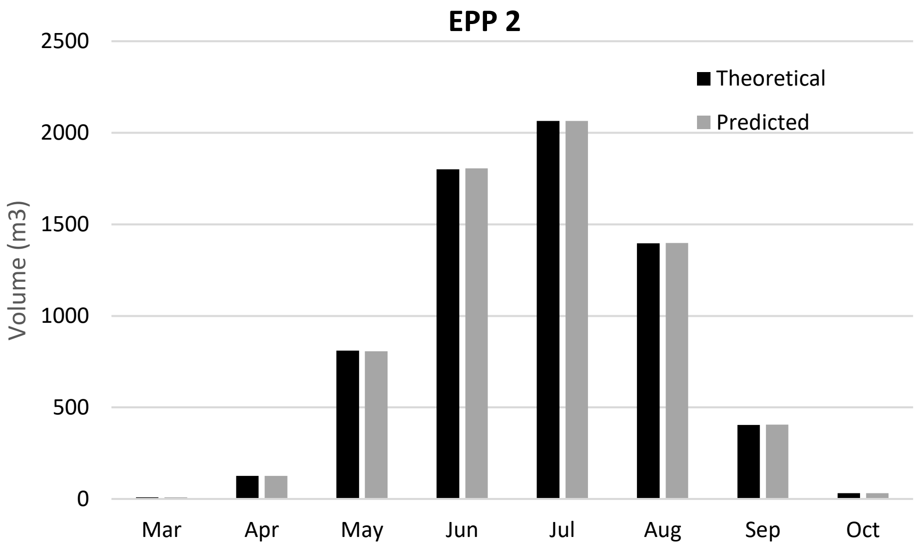

Figure A.2-4. *Monthly theoretical irrigation crop requirements vs predicted crop irrigation requirements for the EPP 2*

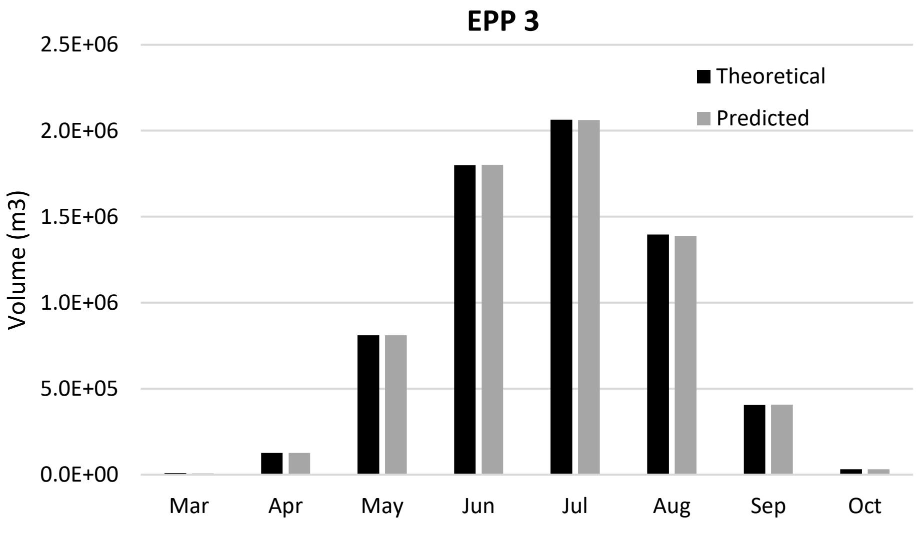

Figure A.2-5. *Monthly theoretical irrigation crop requirements vs predicted crop irrigation requirements for the EPP 3*

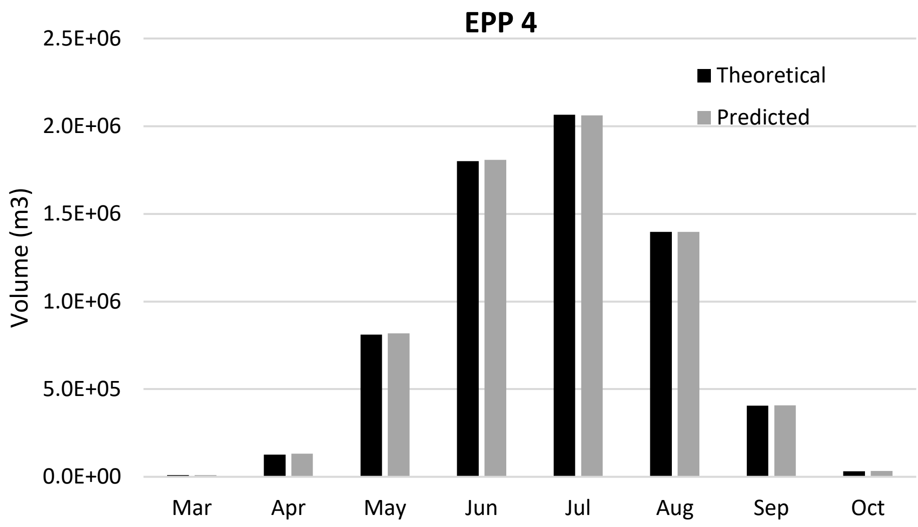

Figure A.2-6. *Monthly theoretical irrigation crop requirements vs predicted crop irrigation requirements for the EPP 4*

Appendix B: Chapter 5 Further Details

B.1. Annual mass probability function Figures for predicted and actual flow values.

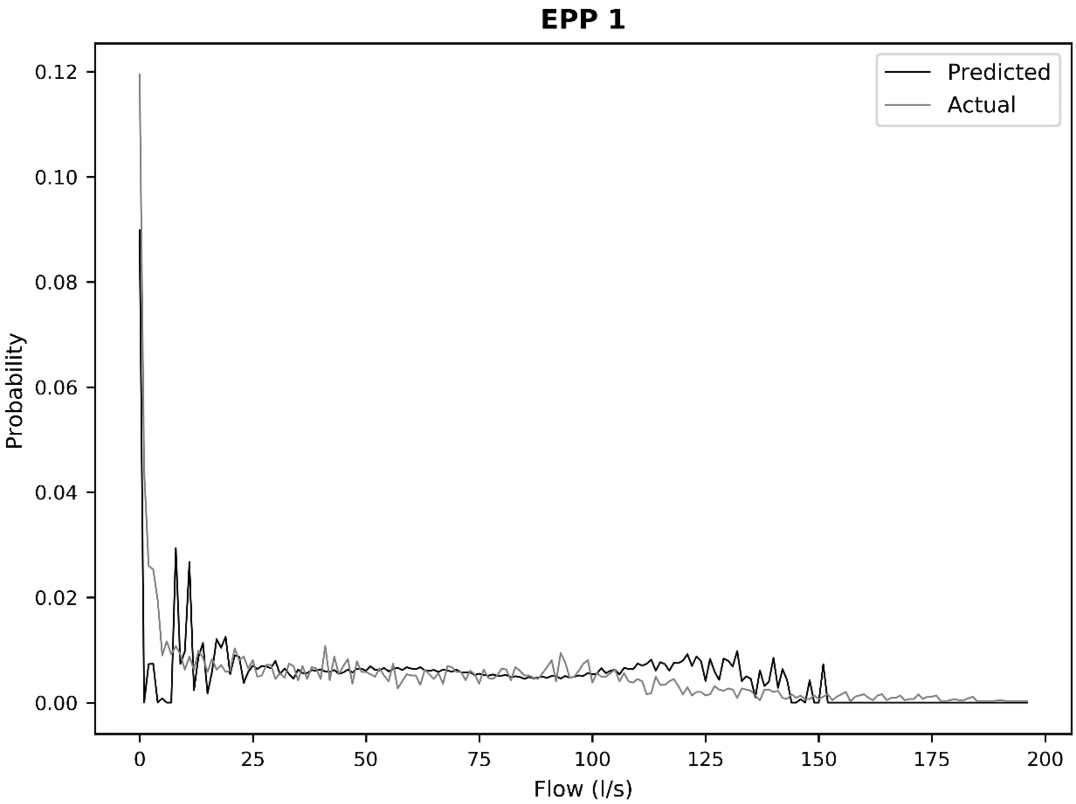

Figure B.1-1. *Annual mass probability function values for predicted and actual flow domains for EPP 1*

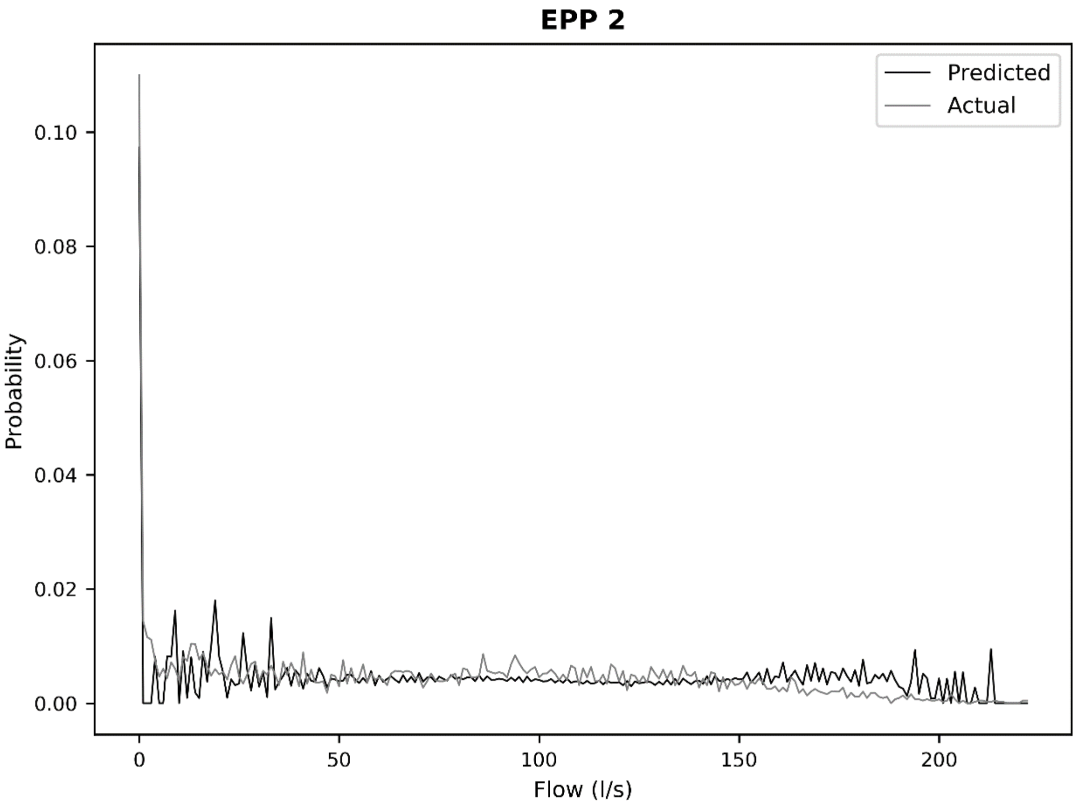

Figure B.1-2. *Annual mass probability function values for predicted and actual flow domains for EPP 2*

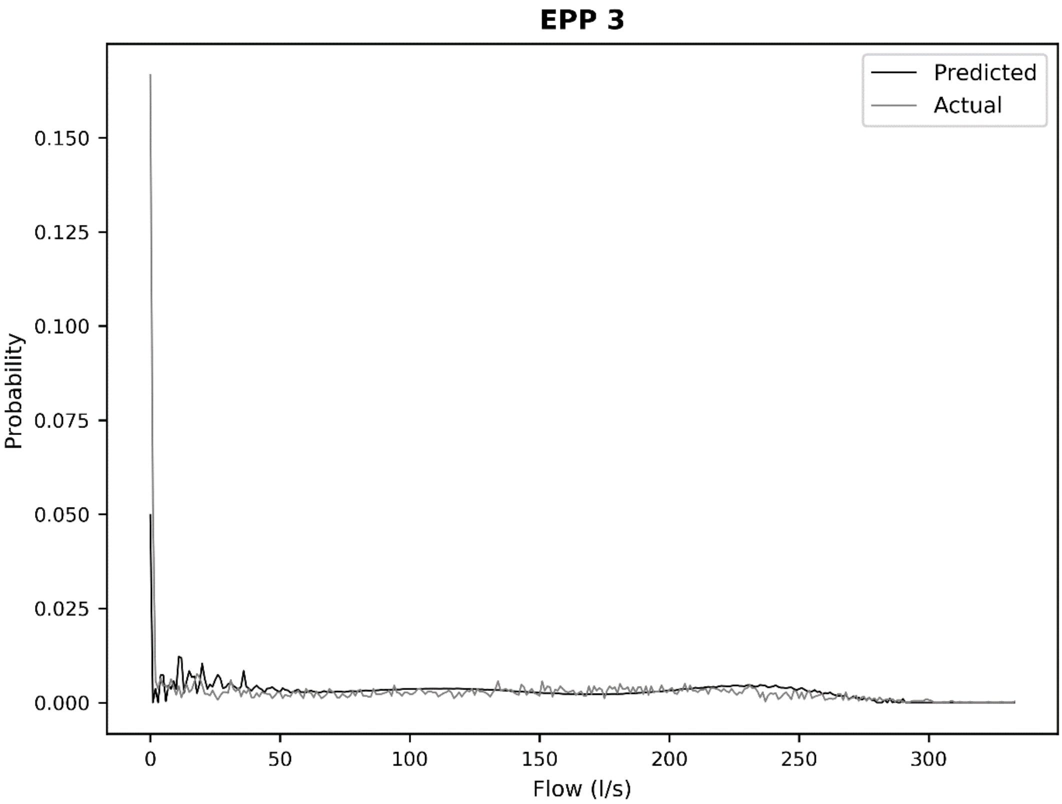

Figure B.1-3. *Annual mass probability function values for predicted and actual flow domains for EPP 3*

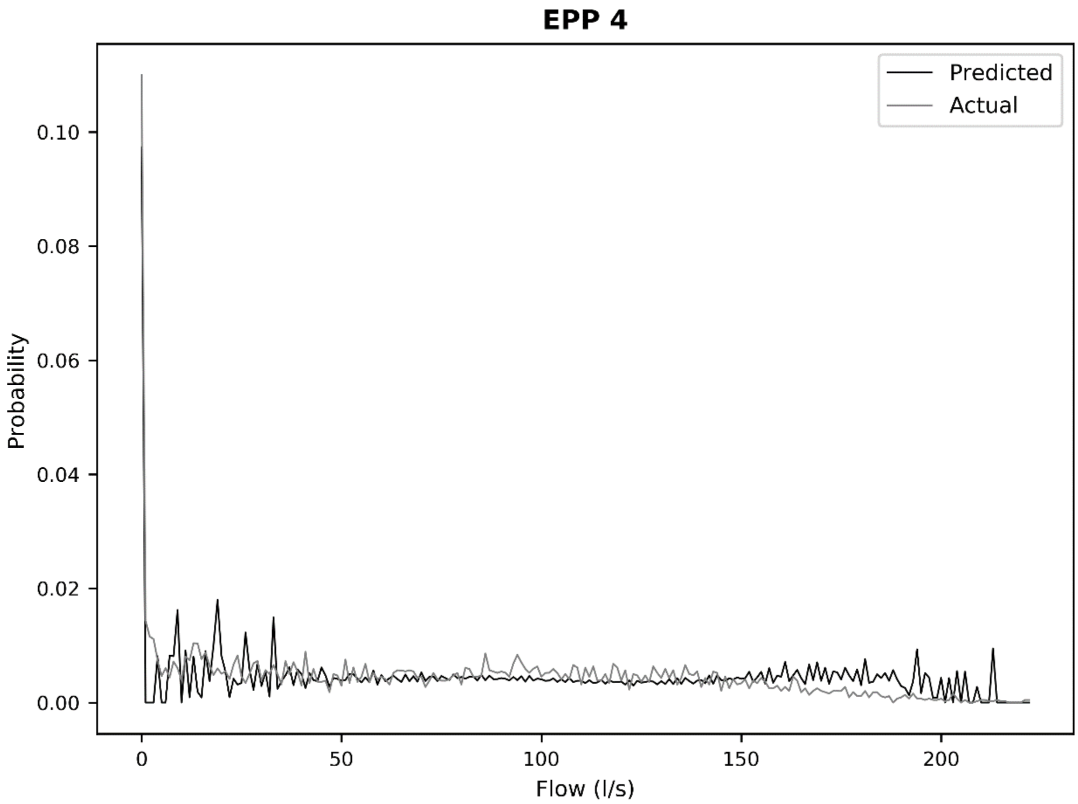

Figure B.1-4. *Annual mass probability function values for predicted and actual flow domains for EPP 4*

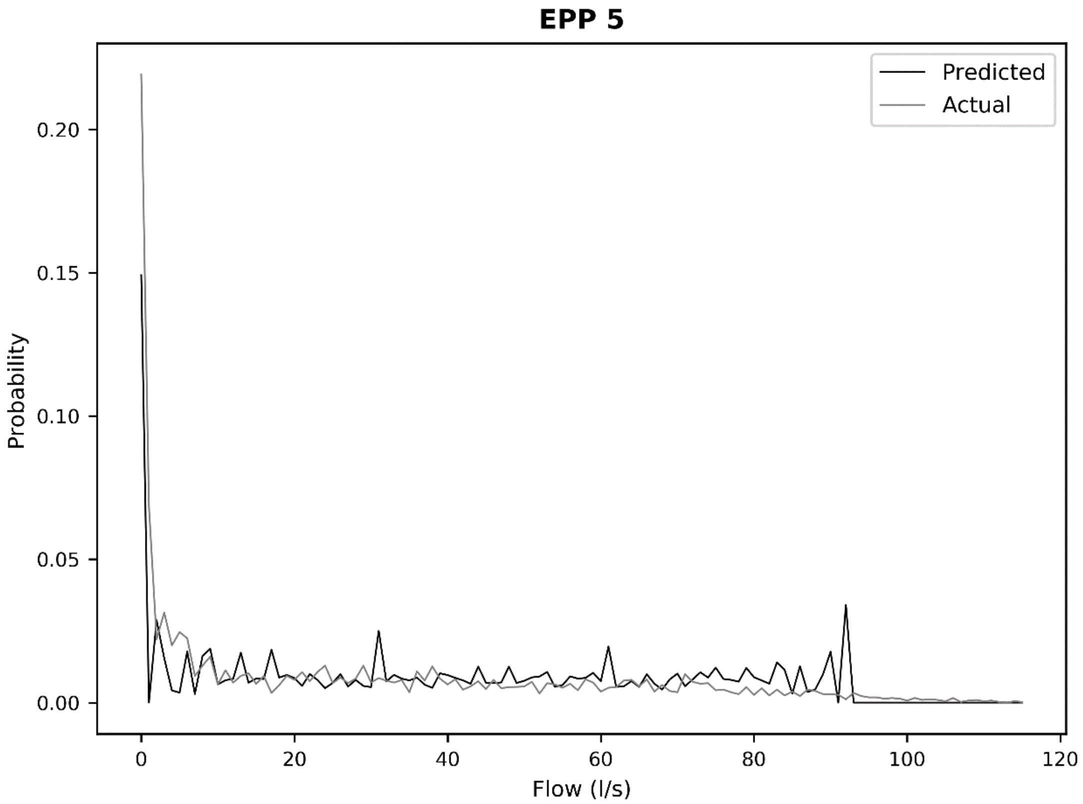

Figure B.1-5. *Annual mass probability function values for predicted and actual flow domains for EPP 5*

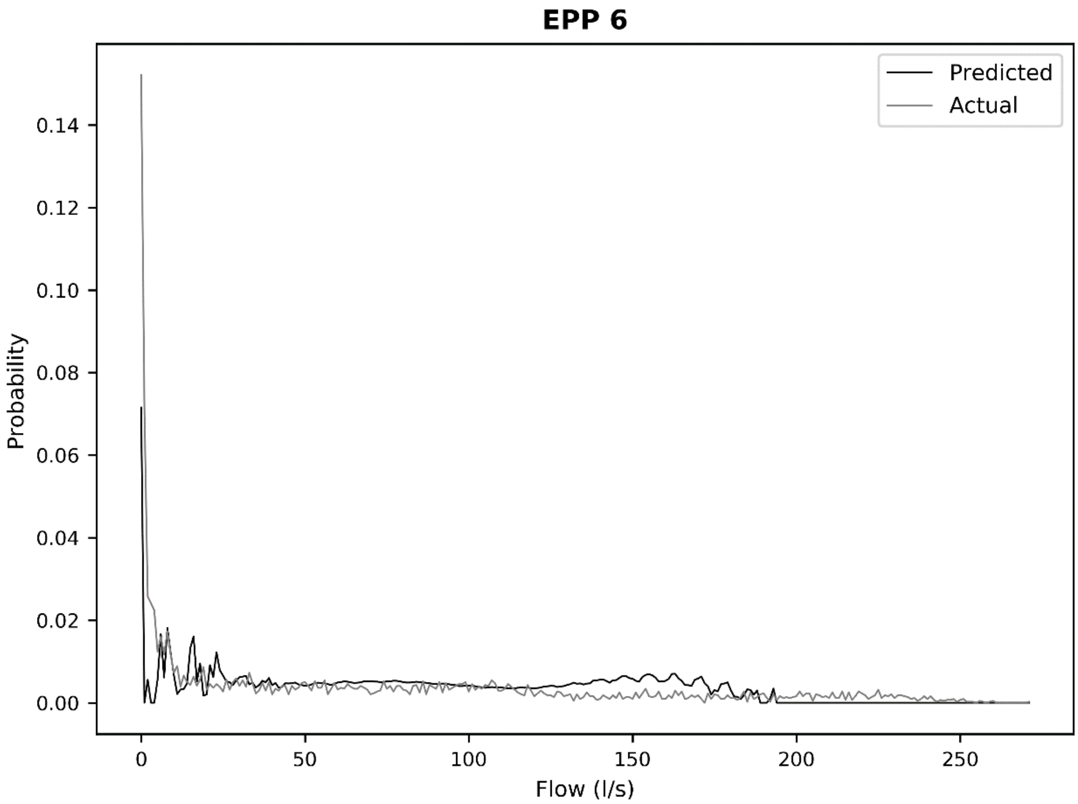

Figure B.1-6. *Annual mass probability function values for predicted and actual flow domains for EPP 6*

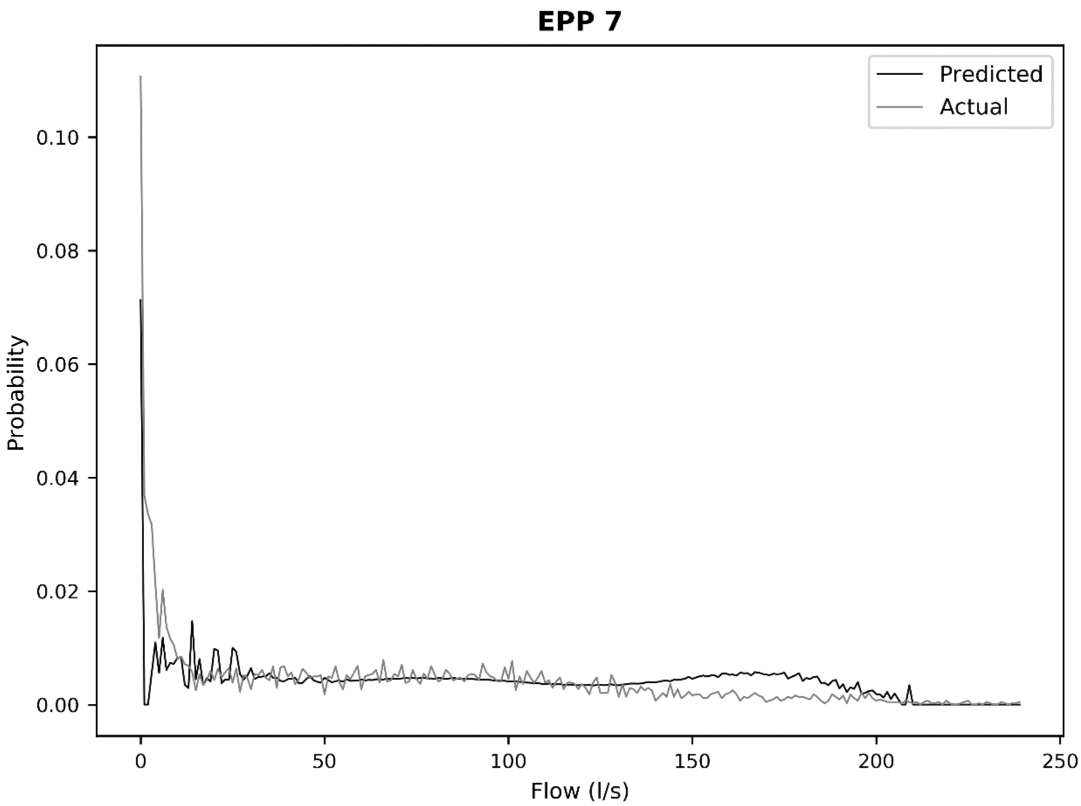

Figure B.1-7. *Annual mass probability function values for predicted and actual flow domains for EPP 7*

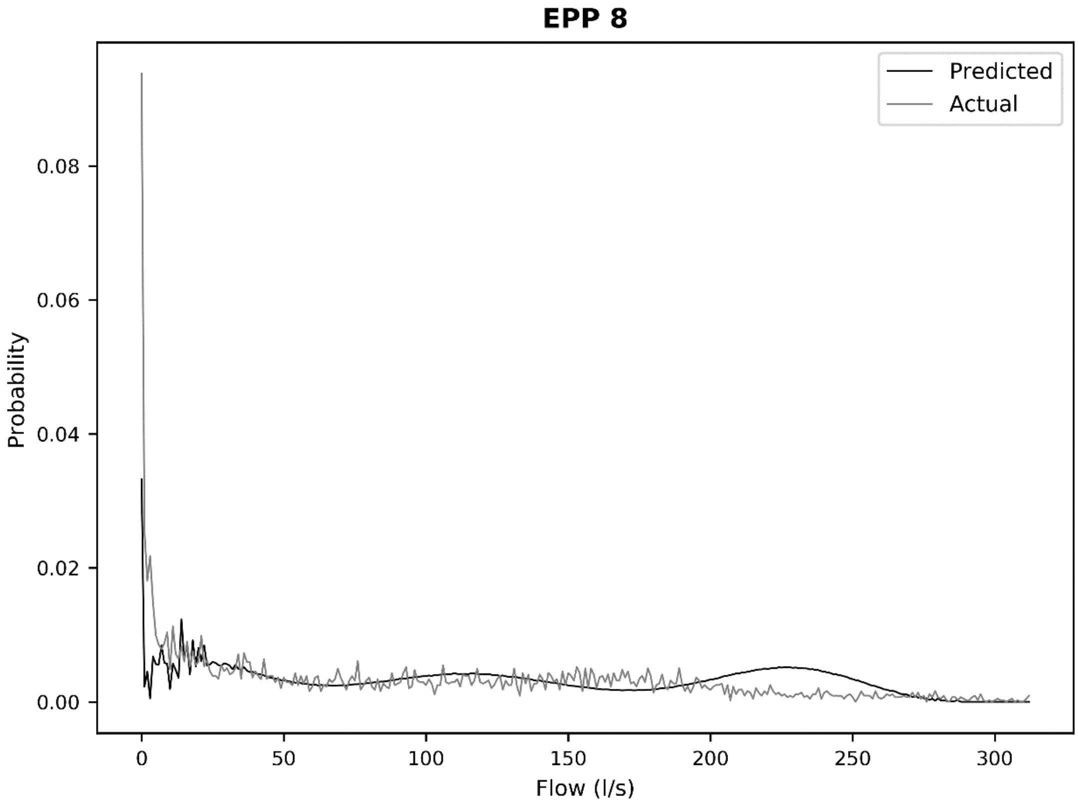

Figure B.1-8. *Annual mass probability function values for predicted and actual flow domains for EPP 8*

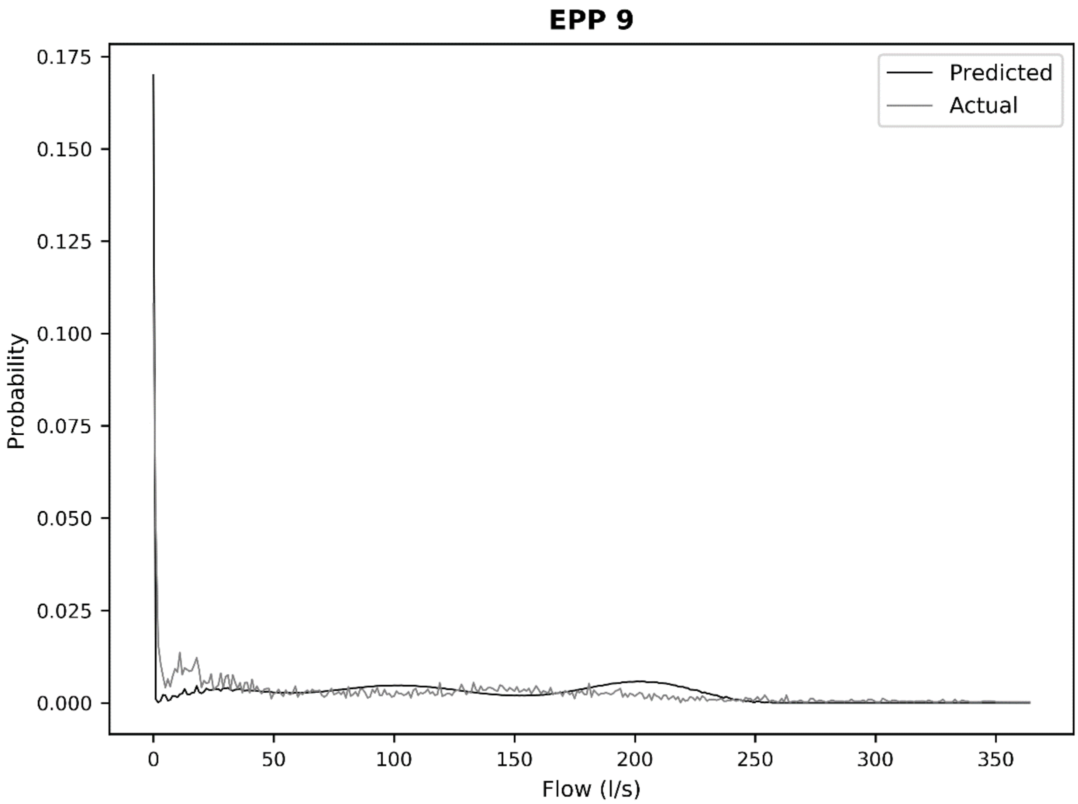

Figure B.1-9. *Annual mass probability function values for predicted and actual flow domains for EPP 9*

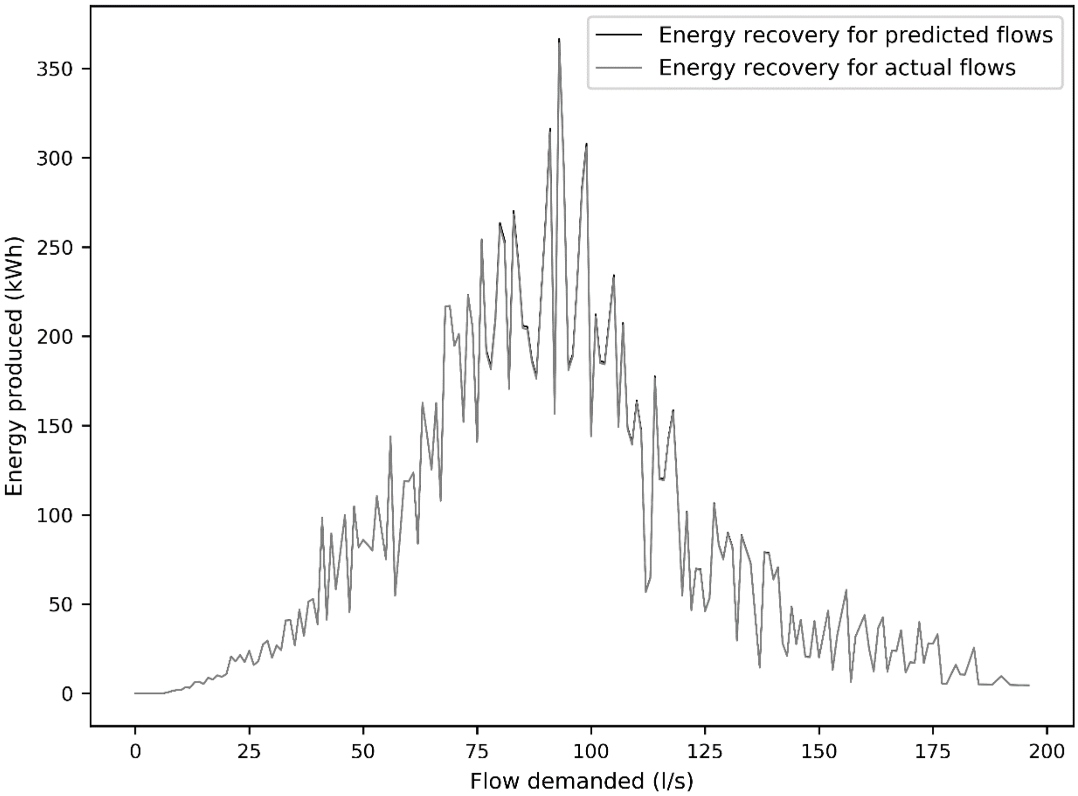

Figure B.2-1. *Potential energy recovery comparison for each flow between predicted and actual conditions EPP 1*

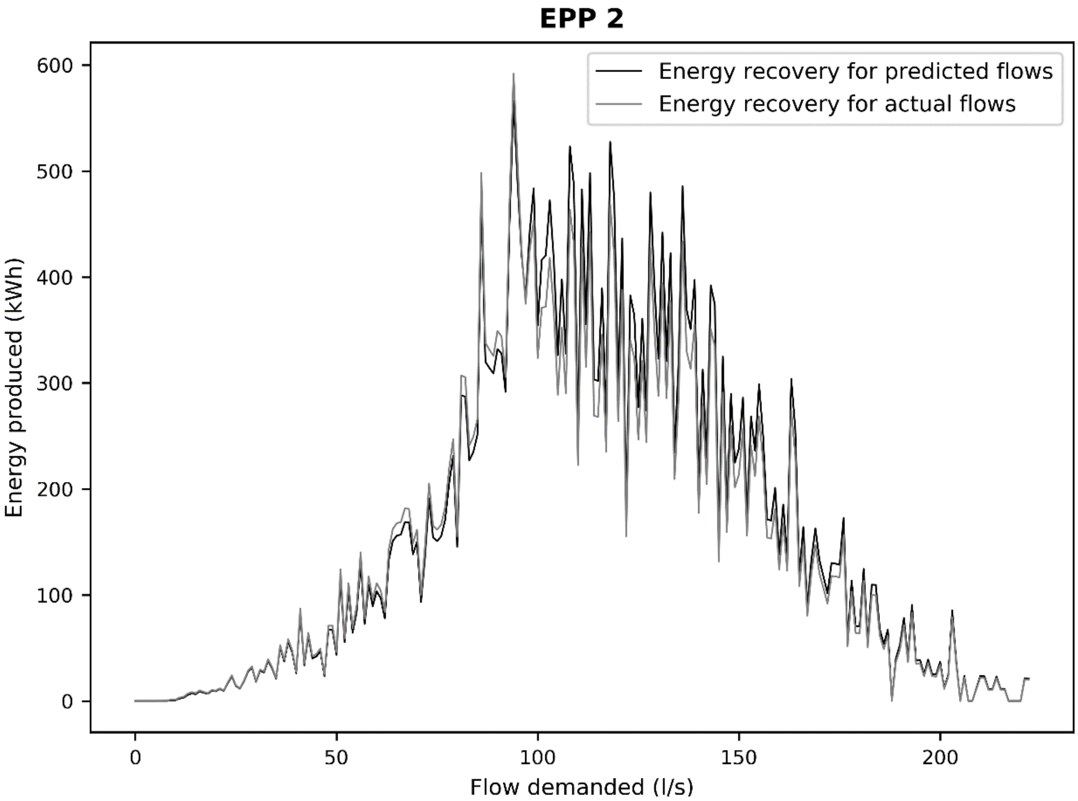

Figure B.2-2. *Potential energy recovery comparison for each flow between predicted and actual conditions EPP 2*

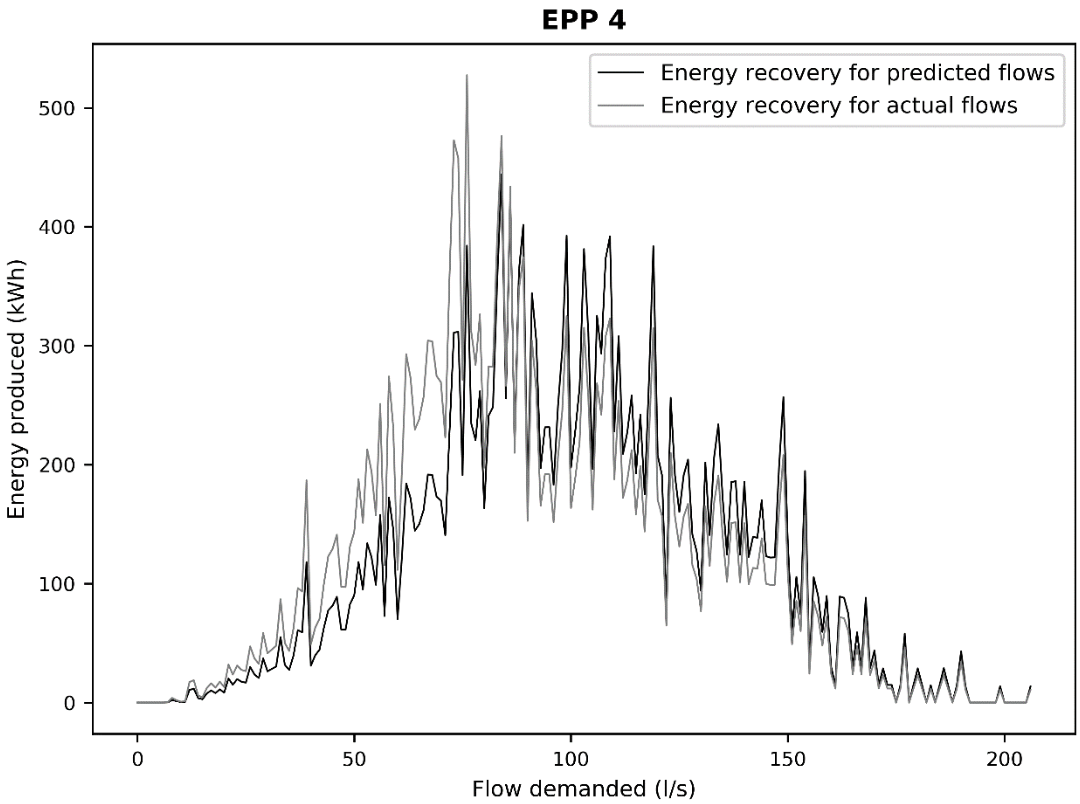

Figure B.2-3. *Potential energy recovery comparison for each flow between predicted and actual conditions EPP 4*

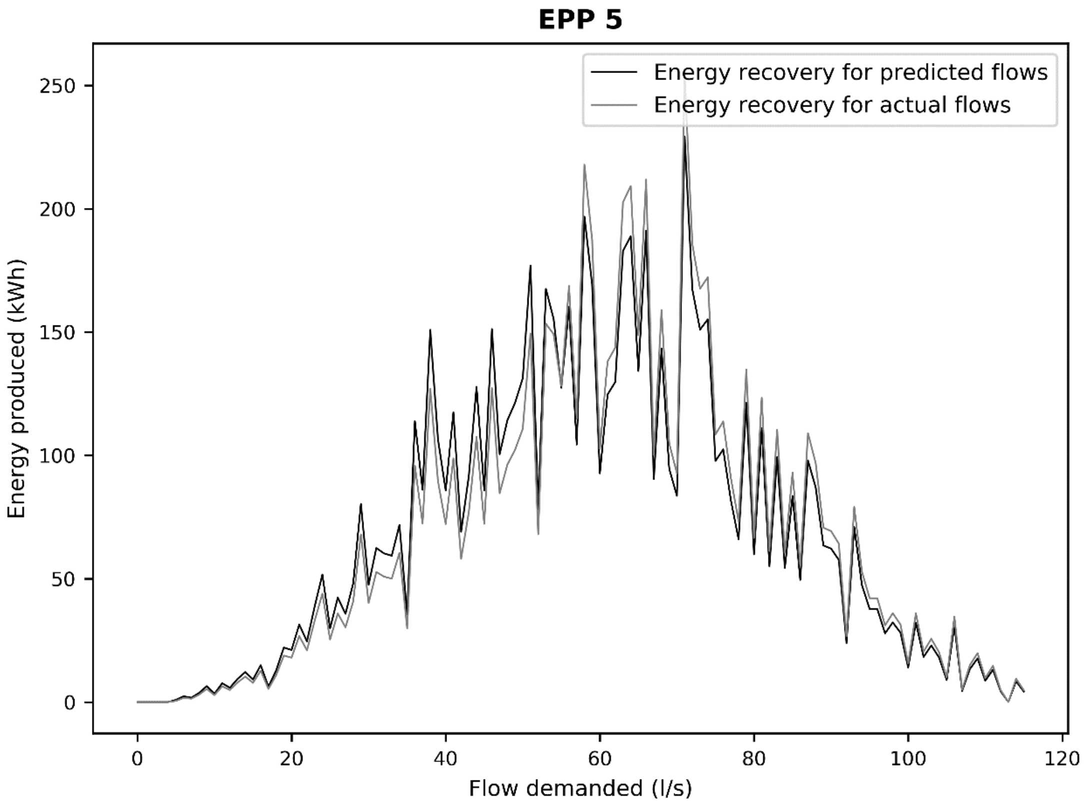

Figure B.2-4. *Potential energy recovery comparison for each flow between predicted and actual conditions EPP 5*

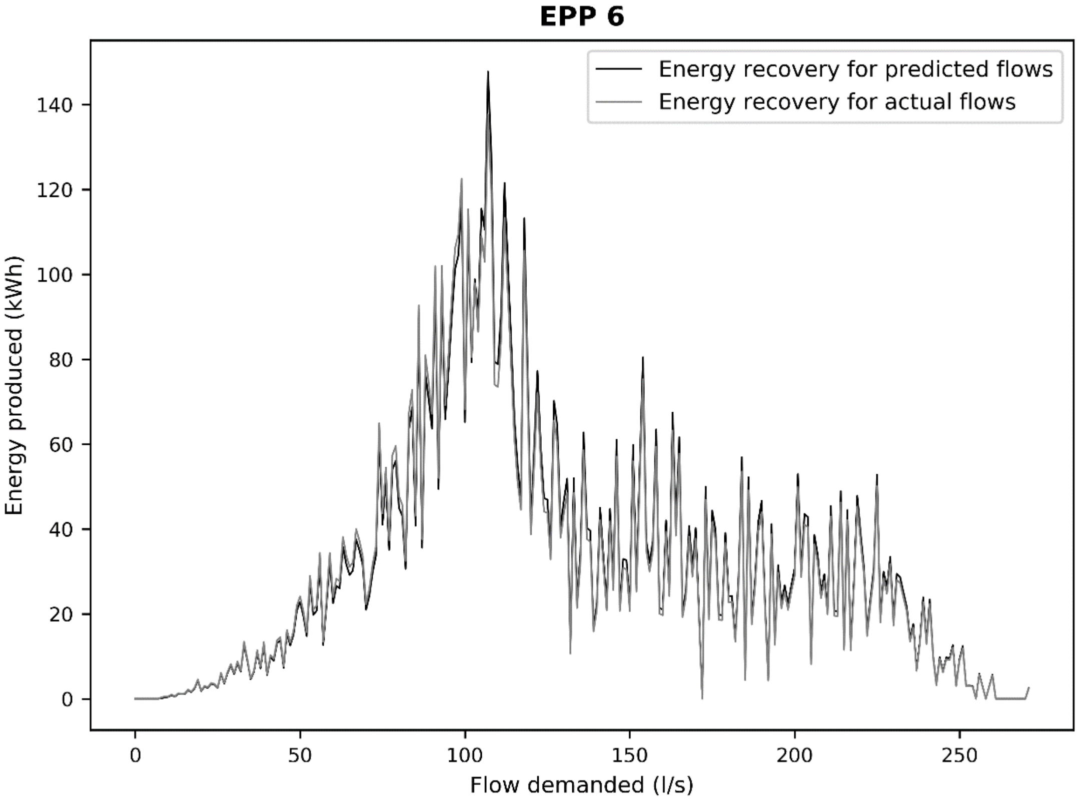

Figure B.2-5. *Potential energy recovery comparison for each flow between predicted and actual conditions EPP 6*

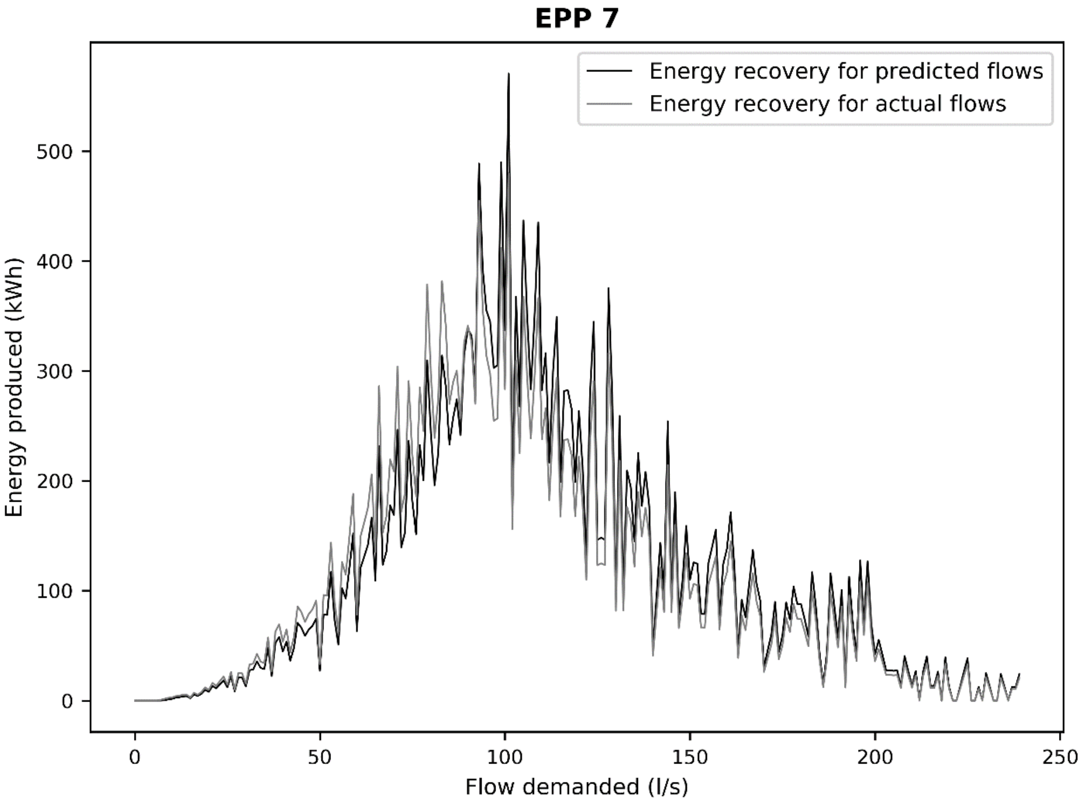

Figure B.2-6. *Potential energy recovery comparison for each flow between predicted and actual conditions EPP 7*

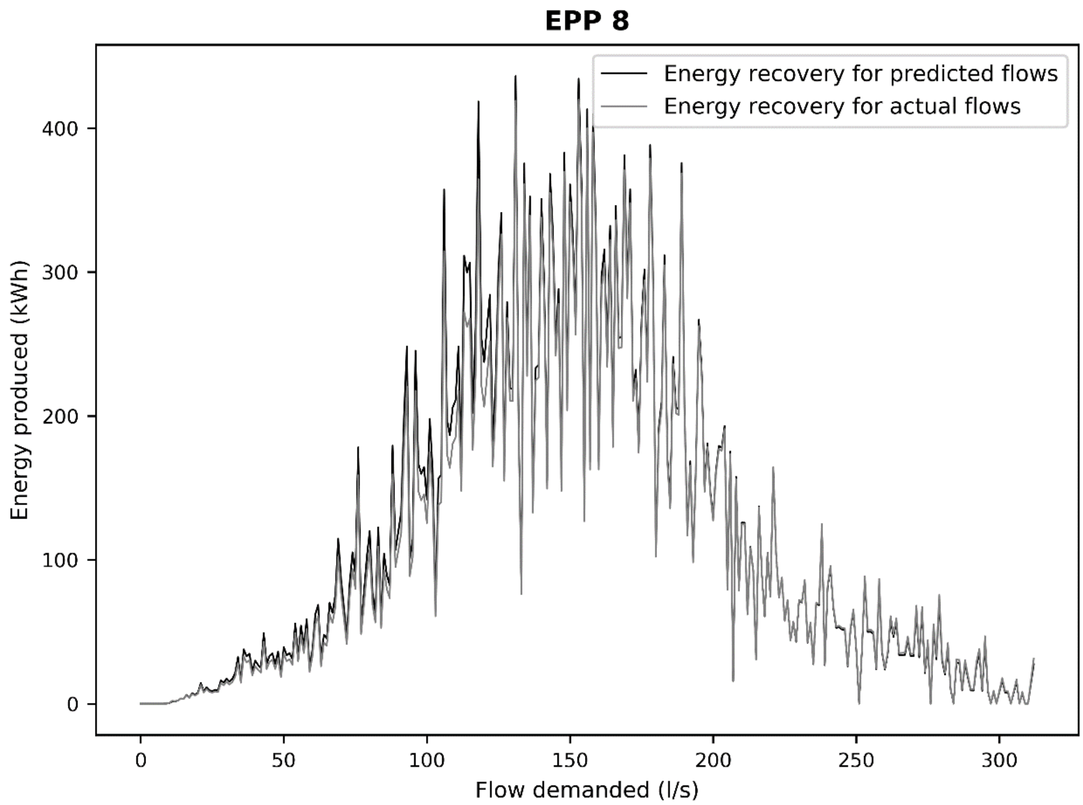

Figure B.2-7. *Potential energy recovery comparison for each flow between predicted and actual conditions EPP 8*

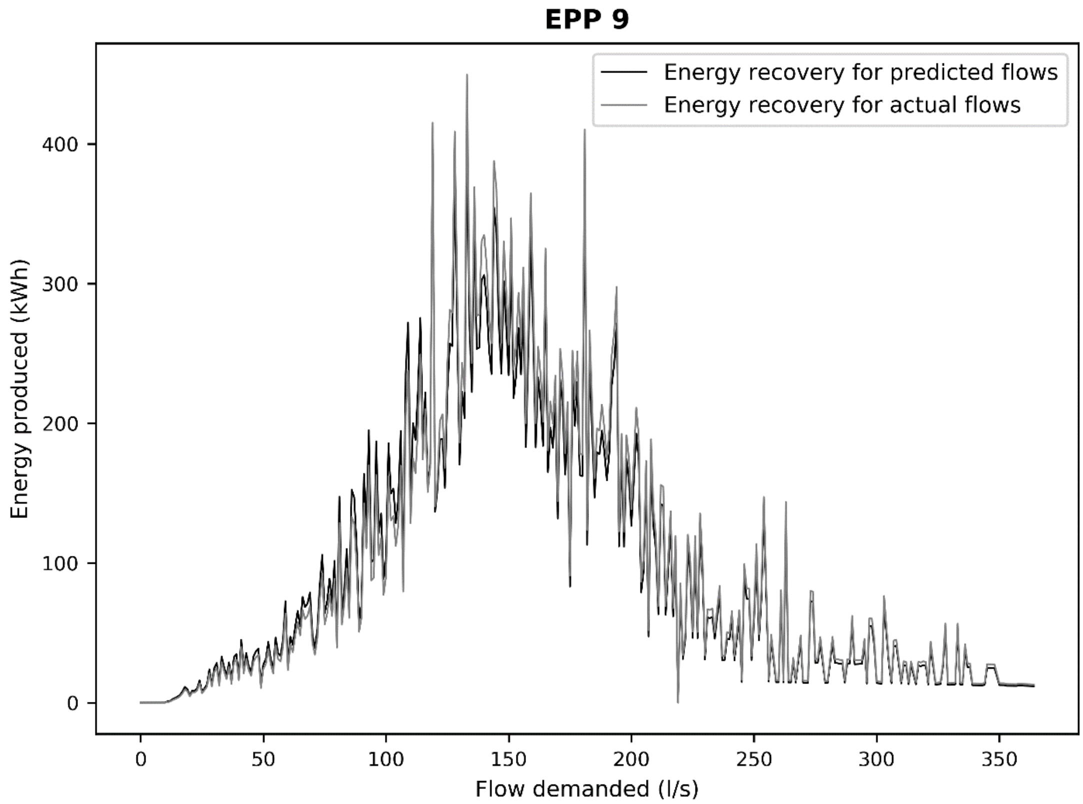

Figure B.2-8. *Potential energy recovery comparison for each flow between predicted and actual conditions EPP 9*

Appendix C: Chapter 6 Further Details

C.1. Input proxy variables and output predicted for each municipality

Municipality	Province	Surface (ha)	log(IR)	Slope (%)	Energy (MWh)
Adamuz	Córdoba	1093.54	6.00	3.67	199.69
Aguadulce	Sevilla	149.63	6.98	1.92	38.37
Aguilar de la Frontera	Córdoba	1043.48	6.78	12.04	188.61
Alanís	Sevilla	0.64	6.38	15.74	4.13
Albaida del Aljarafe	Sevilla	4.97	7.77	5.29	5.91
Alcalá de Guadaíra	Sevilla	1474.98	5.59	2.88	256.83
Alcalá del Río	Sevilla	1299.30	6.69	10.27	227.07
Alcaracejos	Córdoba	30.92	3.51	4.82	13.95
Alcolea del Río	Sevilla	1199.80	5.78	10.11	212.75
Algaba (La)	Sevilla	553.99	7.00	5.26	100.39
Algámitas	Sevilla	2.79	6.36	2.31	6.59
Almadén de la Plata	Sevilla	1.11	6.64	10.60	10.62
Almedinilla	Córdoba	24.79	6.80	8.56	12.91
Almensilla	Sevilla	68.09	3.93	3.74	22.44
Almodóvar del Río	Córdoba	1953.27	4.52	5.23	339.86
Añora	Córdoba	2.33	5.26	7.36	7.23
Arahal	Sevilla	870.41	7.05	13.15	155.01
Aznalcázar	Sevilla	1814.68	5.09	0.30	314.01
Aznalcóllar	Sevilla	178.71	5.87	8.57	46.07
Badolatosa	Sevilla	507.22	5.76	6.24	109.64
Baena	Córdoba	3073.08	5.10	13.29	532.76
Belalcázar	Córdoba	55.18	7.01	2.82	20.36
Belmez	Córdoba	441.97	6.95	2.52	91.66
Benacazón	Sevilla	713.99	6.11	4.86	128.89
Benamejí	Córdoba	358.36	7.10	6.34	80.99
Blázquez (Los)	Córdoba	12.41	4.14	13.00	8.81
Bollullos de la Mitación	Sevilla	929.97	6.11	13.97	165.42
Bormujos	Sevilla	62.27	6.77	7.15	21.51
Brenes	Sevilla	870.70	0.00	0.00	153.69

Bujalance	Córdoba	543.94	6.87	5.70	111.14
Burguillos	Sevilla	659.12	4.13	25.55	122.40
Cabezas de San Juan (Las)	Sevilla	367.27	5.42	12.86	75.04
Cabra	Córdoba	235.68	6.59	0.98	59.93
Camas	Sevilla	0.52	5.86	9.43	4.03
Campana (La)	Sevilla	1128.12	6.63	5.56	198.68
Cañada Rosal	Sevilla	207.15	6.10	1.73	44.35
Cañete de las Torres	Córdoba	11.25	7.27	12.61	9.31
Cantillana	Sevilla	1968.24	7.46	4.90	341.06
Carcabuey	Córdoba	61.76	4.23	10.40	22.51
Cardeña	Córdoba	0.16	5.52	6.73	6.95
Carlota (La)	Córdoba	385.52	3.85	25.94	75.43
Carmona	Sevilla	6623.42	6.39	7.42	1121.99
Carpio (El)	Córdoba	405.23	6.44	9.12	81.64
Carrión de los Céspedes	Sevilla	10.57	6.91	6.13	7.38
Casariche	Sevilla	593.02	3.68	6.30	109.81
Castilblanco de los Arroyos	Sevilla	369.74	6.43	5.24	80.21
Castilleja de Guzmán	Sevilla	0.00	4.00	4.31	0.71
Castilleja de la Cuesta	Sevilla	0.00	5.52	2.54	0.71
Castilleja del Campo	Sevilla	67.10	6.11	2.71	23.15
Castillo de las Guardas (El)	Sevilla	15.95	7.05	6.75	9.22
Castro del Río	Córdoba	1220.06	5.60	2.94	218.65
Cazalla de la Sierra	Sevilla	6.36	4.22	34.25	7.92
Conquista	Córdoba	0.47	6.28	10.73	4.69
Constantina	Sevilla	96.17	6.13	5.46	29.99
Córdoba	Córdoba	4132.89	4.81	8.76	706.88
Coria del Río	Sevilla	342.12	6.03	15.48	64.99
Coripe	Sevilla	0.36	7.44	4.21	5.44
Coronil (El)	Sevilla	34.74	6.47	2.28	14.88
Corrales (Los)	Sevilla	228.13	7.29	7.57	56.68
Cuervo de Sevilla (El)	Sevilla	26.72	5.26	2.38	12.42
Doña Mencía	Córdoba	3.53	6.77	2.67	8.66
Dos Hermanas	Sevilla	1587.16	3.24	19.45	274.94

Dos Torres	Córdoba	25.85	6.54	11.61	12.40
Écija	Sevilla	9654.68	6.84	8.21	1633.23
Encinas Reales	Córdoba	17.81	7.08	2.95	9.96
Espartinas	Sevilla	60.03	5.35	16.62	20.63
Espejo	Córdoba	132.75	6.04	5.84	38.23
Espiel	Córdoba	1.64	6.10	9.33	8.34
Estepa	Sevilla	1500.08	6.31	4.16	262.91
Fernán-Núñez	Córdoba	50.13	4.84	11.82	19.39
Fuente la Lancha	Córdoba	0.59	6.53	14.40	4.21
Fuente Obejuna	Córdoba	488.55	5.50	15.95	93.21
Fuente Palmera	Córdoba	2063.30	6.63	3.05	356.13
Fuentes de Andalucía	Sevilla	368.84	4.66	7.58	70.29
Fuente-Tójar	Córdoba	12.73	2.85	15.95	7.97
Garrobo (El)	Sevilla	1.29	5.47	4.78	4.29
Gelves	Sevilla	18.90	7.00	4.07	9.92
Gerena	Sevilla	226.18	7.46	9.53	51.87
Gilena	Sevilla	883.93	4.53	9.01	160.69
Gines	Sevilla	0.00	5.96	6.29	0.71
Granjuela (La)	Córdoba	17.81	6.73	3.24	9.99
Guadalcanal	Sevilla	45.72	4.48	9.04	18.08
Guadalcázar	Córdoba	1871.38	5.55	4.45	326.39
Guijo (El)	Córdoba	0.00	6.37	4.08	0.71
Guillena	Sevilla	697.10	6.35	6.90	127.97
Herrera	Sevilla	1345.69	4.14	10.86	237.59
Hinojosa del Duque	Córdoba	17.88	6.40	6.20	10.02
Hornachuelos	Córdoba	5444.92	6.63	1.03	925.56
Huévar del Aljarafe	Sevilla	461.34	5.87	2.42	88.87
Isla Mayor	Sevilla	10.34	4.73	0.69	7.40
Iznájar	Córdoba	56.58	6.63	6.59	23.03
Lantejuela (La)	Sevilla	56.16	4.96	10.90	19.62
Lebrija	Sevilla	199.32	5.38	2.95	44.63
Lora de Estepa	Sevilla	201.27	5.61	6.45	49.02
Lora del Río	Sevilla	4085.30	7.06	6.18	696.65
Lucena	Córdoba	173.59	6.87	8.95	48.80
Luisiana (La)	Sevilla	475.67	3.52	8.61	88.19
Luque	Córdoba	398.11	3.39	7.05	94.68
Madroño (El)	Sevilla	0.29	6.42	8.60	8.24
Mairena del Alcor	Sevilla	279.30	5.65	4.56	59.20

Mairena del Aljarafe	Sevilla	51.67	6.65	7.37	19.13
Marchena	Sevilla	1618.52	2.51	17.17	281.86
Marinaleda	Sevilla	137.37	7.32	4.09	38.73
Martín de la Jara	Sevilla	335.09	3.72	5.23	71.85
Molares (Los)	Sevilla	104.71	6.46	1.14	29.52
Montalbán de Córdoba	Córdoba	802.92	6.41	5.66	149.74
Montellano	Sevilla	33.21	4.64	9.08	14.29
Montemayor	Córdoba	98.96	3.41	4.76	31.20
Montilla	Córdoba	613.06	7.44	7.21	120.45
Montoro	Córdoba	2012.91	4.26	17.04	355.06
Monturque	Córdoba	140.13	6.83	3.09	39.95
Moriles	Córdoba	93.77	5.19	7.01	29.11
Morón de la Frontera	Sevilla	1889.73	4.84	2.82	329.04
Navas de la Concepción (Las)	Sevilla	0.70	4.60	18.56	5.29
Nueva Carteya	Córdoba	212.93	6.99	4.73	57.38
Obejo	Córdoba	2.44	4.95	3.74	10.81
Olivares	Sevilla	122.93	6.29	5.03	34.49
Osuna	Sevilla	3129.40	4.59	3.13	535.90
Palacios y Villafranca (Los)	Sevilla	483.97	6.61	7.57	88.68
Palenciana	Córdoba	118.67	7.51	2.81	35.45
Palma del Río	Córdoba	4515.06	4.82	2.85	769.37
Palomares del Río	Sevilla	12.28	4.42	8.97	8.08
Paradas	Sevilla	288.15	5.12	3.89	61.80
Pedrera	Sevilla	605.31	5.54	5.27	114.73
Pedro Abad	Córdoba	380.65	5.84	8.26	79.66
Pedroche	Córdoba	0.87	3.93	17.66	4.71
Pedroso (El)	Sevilla	26.28	6.92	4.36	12.40
Peñaflor	Sevilla	1317.85	4.28	19.44	231.57
Peñarroya-Pueblonuevo	Córdoba	1.85	6.60	4.71	4.59
Pilas	Sevilla	470.97	6.44	3.77	88.54
Posadas	Córdoba	1876.33	5.49	11.58	327.22
Pozoblanco	Córdoba	2.75	6.23	9.07	13.49
Priego de Córdoba	Córdoba	210.39	0.00	0.00	57.12
Pruna	Sevilla	14.45	4.94	17.14	11.52
Puebla de Cazalla (La)	Sevilla	741.38	6.65	9.36	138.71

Puebla de los Infantes (La)	Sevilla	134.30	5.83	9.79	38.93
Puebla del Río (La)	Sevilla	116.99	5.83	3.89	33.08
Puente Genil	Córdoba	3188.47	3.54	5.06	548.40
Rambla (La)	Córdoba	1135.70	0.00	0.00	203.88
Real de la Jara (El)	Sevilla	0.70	3.56	27.21	10.79
Rinconada (La)	Sevilla	2342.60	7.18	1.16	401.44
Roda de Andalucía (La)	Sevilla	594.56	6.60	3.96	109.48
Ronquillo (El)	Sevilla	0.12	2.84	13.59	6.26
Rubio (El)	Sevilla	26.66	5.25	2.45	12.41
Rute	Córdoba	42.63	6.47	5.31	17.78
Salteras	Sevilla	117.32	5.88	3.89	33.19
San Juan de Aznalfarache	Sevilla	0.00	0.00	0.00	0.71
San Nicolás del Puerto	Sevilla	0.00	0.00	0.00	0.71
San Sebastián de los Ballesteros	Córdoba	7.53	5.62	6.43	7.23
Sanlúcar la Mayor	Sevilla	410.32	6.41	5.51	81.40
Santa Eufemia	Córdoba	5.69	4.89	4.33	7.05
Santaella	Córdoba	4711.96	7.08	3.44	805.91
Santiponce	Sevilla	50.67	5.53	2.26	18.32
Saucejo (El)	Sevilla	120.29	5.91	15.44	37.11
Sevilla	Sevilla	331.12	6.34	1.31	63.19
Tocina	Sevilla	439.01	6.31	1.17	81.06
Tomares	Sevilla	0.83	3.66	4.36	2.98
Torrecampo	Córdoba	5.22	5.02	6.45	6.90
Umbrete	Sevilla	93.30	5.76	2.03	27.00
Utrera	Sevilla	1964.58	7.07	2.01	338.48
Valencina de la Concepción	Sevilla	26.94	5.15	5.65	12.72
Valenzuela	Córdoba	2.25	4.47	11.96	6.58
Valsequillo	Córdoba	15.22	5.06	4.49	10.10
Victoria (La)	Córdoba	67.29	5.65	8.07	23.19
Villa del Río	Córdoba	482.19	7.07	6.73	97.05
Villafranca de Córdoba	Córdoba	718.40	0.00	0.00	132.98
Villaharta	Córdoba	0.07	6.34	1.26	7.12

Villamanrique de la Condesa	Sevilla	838.58	6.77	2.19	149.30
Villanueva de Córdoba	Córdoba	1.16	3.36	9.57	4.48
Villanueva de San Juan	Sevilla	3.19	4.29	14.19	7.80
Villanueva del Ariscal	Sevilla	23.64	5.18	2.98	11.66
Villanueva del Duque	Córdoba	7.20	5.04	4.08	7.51
Villanueva del Rey	Córdoba	5.86	5.36	4.59	9.71
Villanueva del Río y Minas	Sevilla	1233.82	6.77	4.26	217.26
Villaralto	Córdoba	6.99	7.53	4.81	5.94
Villaverde del Río	Sevilla	1068.10	6.86	5.75	190.66
Villaviciosa de Córdoba	Córdoba	5.12	5.47	26.12	6.81
El Viso	Córdoba	57.11	6.21	7.79	20.54
El Viso del Alcor	Sevilla	85.26	5.79	5.50	27.09
Zuheros	Córdoba	3.64	5.96	14.64	9.39

Appendix D: Chapter 7 Further Details

D.1. Monthly energy recovered vs energy demanded and PAT working conditions.

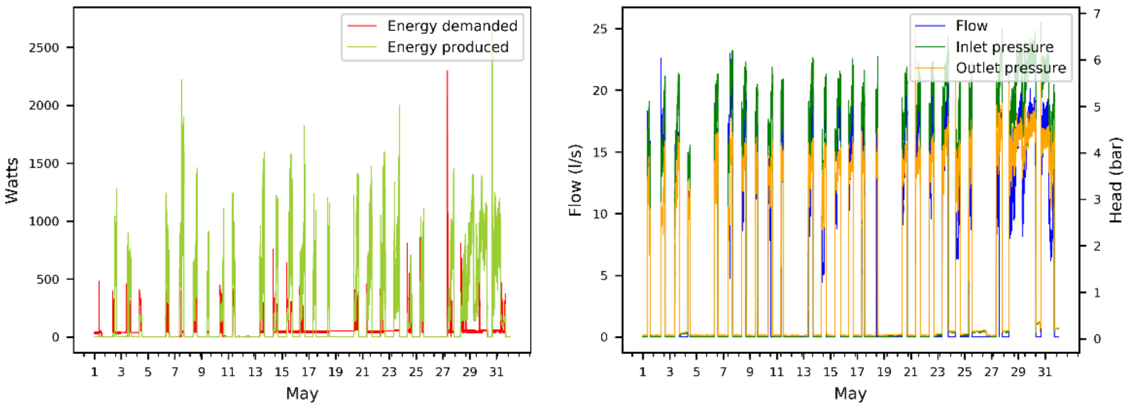

Figure D.1-1. *Energy recovered and demanded at the farm and PAT working conditions (flow – head) for May*

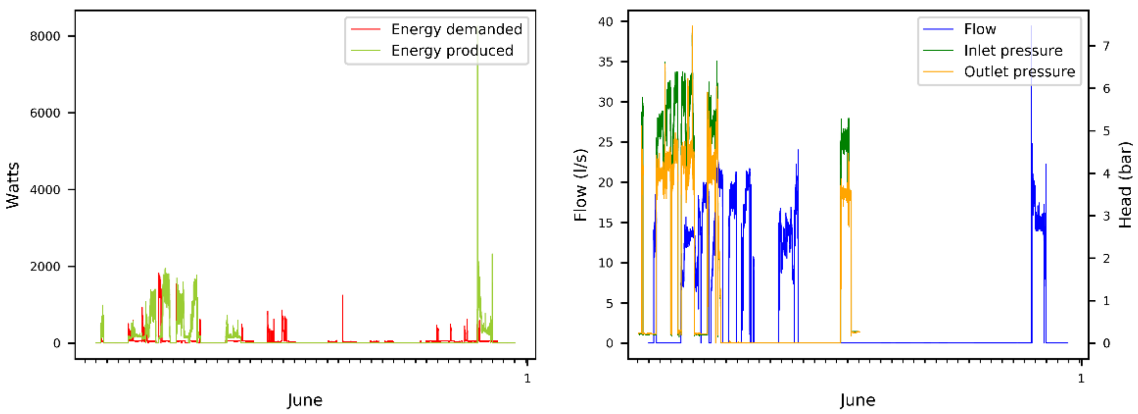

Figure D.1-2. *Energy recovered and demanded at the farm and PAT working conditions (flow – head) for June*

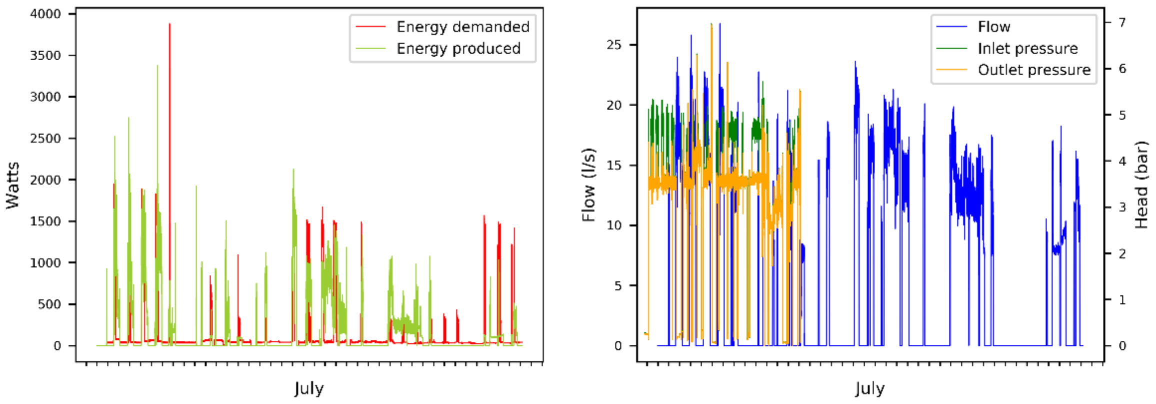

Figure D.1-3. *Energy recovered and demanded at the farm and PAT working conditions (flow – head) for July*

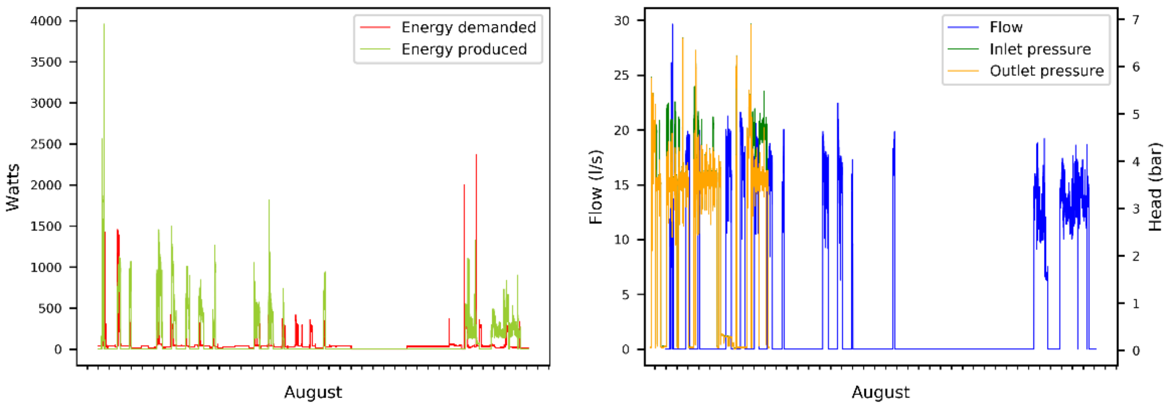

Figure D.1-4. *Energy recovered and demanded at the farm and PAT working conditions (flow – head) for August*

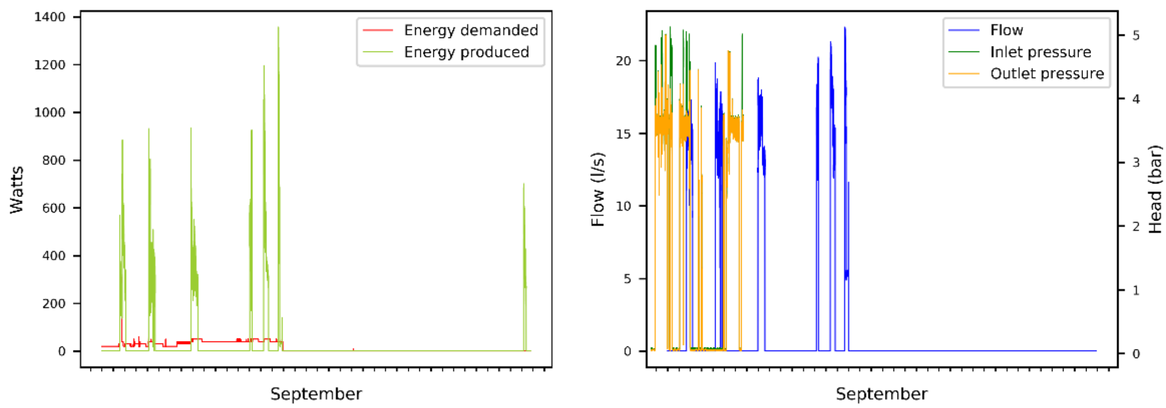

Figure D.1-5. *Energy recovered and demanded at the farm and PAT working conditions (flow – head) for September*

D.1. Technical sheets of the PAT and solar panels

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Turbina hidráulica
Tipo Inline Modelo 080-B

Datos de funcionamiento

Liquido turbinado	Agua Agua limpia No contiene sustancias	Caudal nominal Salto de presión Eficiencia hidráulica	108 m^3/h 20 m 79,7 %
Temperatura ambiente	20,0 °C	Potencia en el eje	4690 W
Temperatura del liquido a turbinar	15,0 °C	Velocidad nominal de rotación de la turbina	1800 rpm
Densidad del fluido	998 kg/m^3	Velocidad de rotación máxima	3000 rpm
Viscosidad del medio a bombear	1,00 mm^2/s	Presión nominal	16,00 bar
Altitud de trabajo	60 m.s.n.m.		

Detalles constructivos

Diseño hidráulico Orientación generador Posición generador Diam. Nominal de salida	Entrada y salida alineadas Eje vertical Exterior no sumergido DN 080	Código de material Se asume funcionamiento con fluido libre de sólidos	BQ1BEGG-WA
Presión nominal brida salida Posición brida de salida	PN 16 En línea		
Brida de salida taladrada de acuerdo con norma	EN 1092-2	Protección del eje	Con
Diám.nominal brida entrada Presión nominal brida entrada	DN 080 PN 16	Anillo rozante Diámetro del rodete	Anillo partido 174,0 mm
Posición de la brida de entrada	En línea	Dirección de rotación del rodete	Antihorario
Brida de entrada taladrada de acuerdo con la norma	EN 1092-2	Acoplamiento del generador	Mediante brida tamaño tipo V1 (IEC)
Cierre del eje Fabricante	GLRD de efecto sencillo KSB	Referencia del cojinete	6413-C3 con anillo nilos AV
Tipo	1	Tipo de cojinete Tipo de lubricación Pintura de la turbina	Rodamiento Grasa (RAL 2002)

Figure D.2-1. *PAT technical sheet.*

Datos del generador

		Clase de aislamiento	F según IEC 34-1
Normativa	IEC	Clase de protección del generador IP 55	
		Coseno phi a plena carga (4/4)	0,89
Generador suministrado por	Tecnoturbines	Rendimiento del generador a plena carga (4/4)	91,0 %
Tipología constructiva del generador	V1 con brida según IEC (montaje con eje en vertical)		
		Bobinado del generador	200 V
Clase de rendimiento	Clase de rendimiento IE3 según IEC60034-30-1		
Velocidad nominal	1500 rpm	Clase de conexión	estrella/triángulo
Voltaje nominal	200 V	Método de refrigeración del generador	Enfriamiento de la superficie mediante ventilador
Potencia nominal	4,00 kW		
Reserva disponible	0 %	Material del generador	Fundición gris

Materiales de la turbina

Criterios para la selección de los materiales:
1.- Agua con un pH de valor>=7
2.- Contenido cloruros (Cl)<=250 mg/kg
3.- Contenido de Cloro (Cl2)<=0.6 mg/kg

		Rodete	Fundición gris EN-GJL-250
		Pieza acoplamiento del generador	Fundición gris EN-GJL-250
Voluta	Fundición esferolítica EN-GJS-400-18-LT	Anillos de descaste	Fundición gris GG/CAST IRON
Tapa de la voluta	Fundición gris EN-GJL-250		
Eje	Acero bonificado C45+N		

Figure D.2-2. *Generator technical sheet.*

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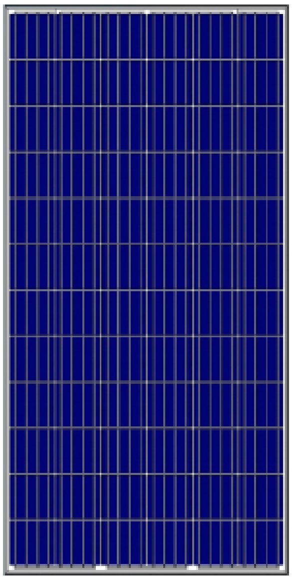
AS-6P



POLYCRYSTALLINE MODULE

ADVANCED PERFORMANCE & PROVEN ADVANTAGES

- High module conversion efficiency up to 17.52% by using high efficient solar cells and advanced manufacturing technology.
- Low degradation and excellent performance under high temperature and low light conditions.
- Robust aluminum frame ensures the modules to withstand wind loads up to 2400Pa and snow loads up to 5400Pa.
- High reliability against extreme environmental conditions (passing salt mist, ammonia and hail tests).
- Potential induced degradation (PID) resistance.
- Positive power tolerance of 0 ~ +3 %.

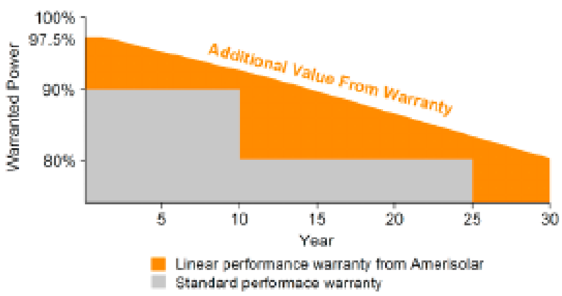
CERTIFICATIONS

- IEC61215, IEC61730, IEC62716, IEC61701, CE, CQC, CGC, ETL(USA), JET(Japan), J-PEC(Japan), Kemco(South Korea), KS(South Korea), MCS(UK), CEC(Australia), FSEC(FL-USA), CSI Eligible(CA-USA), Israel Electric(Israel), InMetro(Brazil), TSE(Turkey)
- ISO9001:2008: Quality management system
- ISO14001:2004: Environmental management system
- OHSAS18001:2007: Occupational health and safety management system

Passionately committed to delivering innovative energy solution

SPECIAL WARRANTY

- 12 years limited product warranty.
- Limited linear power warranty: 12 years 91.2% of the nominal power output, 30 years 80.6% of the nominal power output.



ELECTRICAL CHARACTERISTICS AT STC

Nominal Power (P_{max})	300W	305W	310W	315W	320W	325W	330W	335W	340W
Open Circuit Voltage (V_{OC})	45.3V	45.4V	45.5V	45.6V	45.7V	45.8V	45.9V	46.0V	46.1V
Short Circuit Current (I_{SC})	8.68A	8.76A	8.85A	8.93A	9.04A	9.15A	9.26A	9.38A	9.50A
Voltage at Nominal Power (V_{mp})	36.7V	36.8V	36.9V	37.0V	37.1V	37.2V	37.3V	37.4V	37.5V
Current at Nominal Power (I_{mp})	8.18A	8.29A	8.41A	8.52A	8.63A	8.74A	8.85A	8.96A	9.07A
Module Efficiency (%)	15.46	15.72	15.98	16.23	16.49	16.75	17.01	17.26	17.52
Operating Temperature	-40°C to +85°C								
Maximum System Voltage	1000V DC								
Fire Resistance Rating	Type 1(in accordance with UL1703)/Class C(IEC61730)								
Maximum Series Fuse Rating	15A								

STC: Irradiance 1000W/m², Cell temperature 25°C, AM1.5

ELECTRICAL CHARACTERISTICS AT NOCT

Nominal Power (P_{max})	221W	224W	228W	232W	236W	239W	243W	247W	251W
Open Circuit Voltage (V_{OC})	41.7V	41.8V	41.9V	42.0V	42.1V	42.2V	42.3V	42.4V	42.5V
Short Circuit Current (I_{SC})	7.03A	7.10A	7.17A	7.23A	7.32A	7.41A	7.50A	7.60A	7.70A
Voltage at Nominal Power (V_{mp})	33.4V	33.5V	33.6V	33.7V	33.8V	33.9V	34.0V	34.1V	34.2V
Current at Nominal Power (I_{mp})	6.62A	6.69A	6.79A	6.89A	6.98A	7.05A	7.15A	7.25A	7.34A

NOCT: Irradiance 800W/m², Ambient temperature 20°C, Wind Speed 1 m/s

MECHANICAL CHARACTERISTICS

Cell type	Polycrystalline 156x156mm (6x6inches)
Number of cells	72 (6x12)
Module dimensions	1956x992x40mm (77.01x39.06x1.57inches)
Weight	22.5kg (49.6lbs)
Front cover	3.2mm (0.13inches) tempered glass with AR coating
Frame	Anodized aluminum alloy
Junction box	IP67, 3 diodes
Cable	4mm² (0.006inches²), 1000mm (39.37inches)
Connector	MC4 or MC4 compatible

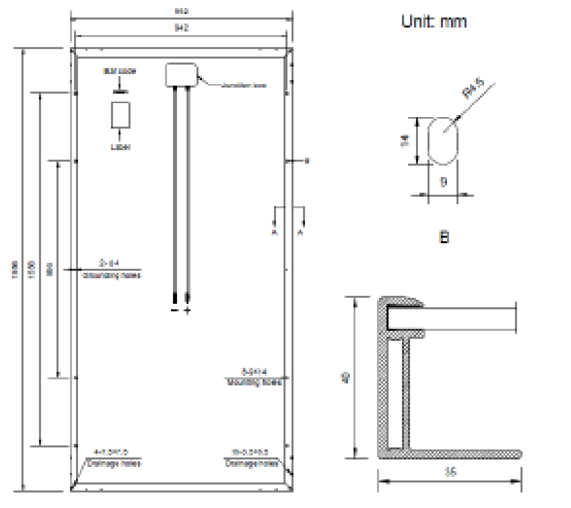
TEMPERATURE CHARACTERISTICS

Nominal Operating Cell Temperature (NOCT)	45°C±2°C
Temperature Coefficients of P_{max}	-0.41%/°C
Temperature Coefficients of V_{oc}	-0.31%/°C
Temperature Coefficients of I_{sc}	0.05%/°C

PACKAGING

Standard packaging	26pcs/pallet
Module quantity per 20' container	260pcs
Module quantity per 40' container	572pcs(GP)/616pcs(HQ)

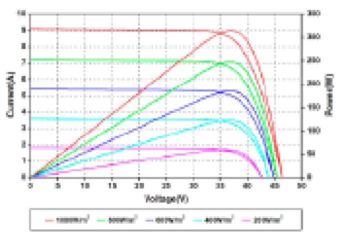
ENGINEERING DRAWINGS



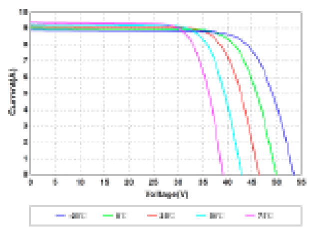
Rear View Section A-A

Specifications in this datasheet are subject to change without prior notice.

IV CURVES



Current-Voltage and Power-Voltage Curves at Different Irradiances



Current-Voltage Curves at Different Temperatures

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Figure D.2-3. *Solar panels technical sheet.*

baterías

Baterías AGM / GEL

Características Generales

- Hermética
- Libre mantenimiento
- Bajo ratio de autodescarga
- Elevada vida útil
- Rango de temperatura: -15 °C a 50 °C
- Rendimiento mejorado: hasta 500 ciclos @80% profundidad de descarga
- Excelente capacidad de recuperación trás una descarga profunda.

Construcción

- Placa positiva: Plana, con bajo contenido en Ca y empastado especial
- Placa negativa: Rejilla compensada Pb-Ca para una mejor recombinación
- Electrolito: Ácido sulfúrico de alta pureza
- Contenedor y tapa en ABS
- Válvula con sistema de seguridad anti explosión integrada.

Aplicaciones típicas:

- Vehículos eléctricos
- Buggies y carros de Golf
- SAI
- Herramientas, juguetes eléctricos
- Energías Renovables
- Telecomunicaciones.

Baterías Monobloc AGM

Modelo	Voltaje	Capacidad Ah 1,80 UPC 20º C	Dimensiones (largo x ancho x alto)	Peso
MEBA12-8	12	8 Ah C_{20}	151 x 66 x 96 (100) mm	2,6 kg
MEBA12-14	12	14 Ah C_{20}	151 x 98 x 95 (100) mm	4.1 kg
MEBA12-20	12	20 Ah C_{20}	181 x 76 x 167 (167) mm	5.8 kg
MEBA12-22	12	22 Ah C_{20}	181 x 76 x 167 (167) mm	6.1 kg
MEBA12-24	12	24 Ah C_{20}	175 x 165 x 125 (125) mm	7.2 kg
MEBA12-26	12	26 Ah C_{20}	165 x 125 x 175 (180) mm	8.0 kg
MEBA12-28	12	28 Ah C_{20}	165 x 125 x 175 (180) mm	8.2 kg
MEBA12-33	12	33 Ah C_{10}	196 x 130 x 157 (200) mm	10.2 kg
MEBA12-38	12	38 Ah C_{10}	197 x 165 x 175 (175) mm	12.2 kg
MEBA12-45	12	45 Ah C_{10}	197 x 165 x 175 (175) mm	13.2 kg
MEBA12-50	12	50 Ah C_{10}	228 x 137 x 207 (213) mm	15.5 kg
MEBA12-55	12	55 Ah C_{10}	228 x 137 x 207 (213) mm	16.5 kg
MEBA12-60	12	60 Ah C_{10}	350 x 166 x 175 (175) mm	18.0 kg
MEBA12-65	12	65 Ah C_{10}	350 x 166 x 175 (175) mm	19.5 kg
MEBA12-70	12	70 Ah C_{10}	260 x 168 x 210 (215) mm	21.0 kg
MEBA12-75	12	75 Ah C_{10}	260 x 168 x 210 (215) mm	22.0 kg
MEBA12-80	12	80 Ah C_{10}	330 x 171 x 217 (220) mm	27.0 kg
MEBA12-90	12	90 Ah C_{10} - 115 Ah C_{100}	330 x 171 x 217 (220)mm	28.0 kg
MEBA12-100	12	100 Ah C_{10} - 125 Ah C_{100}	330 x 171 x 217 (220) mm	29.5 kg
MEBA12-120	12	120 Ah C_{10}	412 x 173 x 237 (237) mm	35.0 kg
MEBA12-150	12	150 Ah C_{10} - 190 Ah C_{100}	484 x 170 x 241 (241) mm	42.5 kg
MEBA12-200	12	200 Ah C_{10}	522 x 240 x 219 (225) mm	59.5 kg
MEBA12-220	12	220 Ah C_{10} - 280 Ah C_{100}	522 x 260 x 220 (225) mm	64.0 kg
MEBA12-250	12	250 Ah C_{10}	522 x 260 x 220 (225) mm	69.0 kg
MEBA6-250	6	250 Ah C_{10}	260 x 180 x 275 (275) mm	35.0 kg

Figure D.2-4. *Batteries technical sheet.*

Appendix E: Technical publications

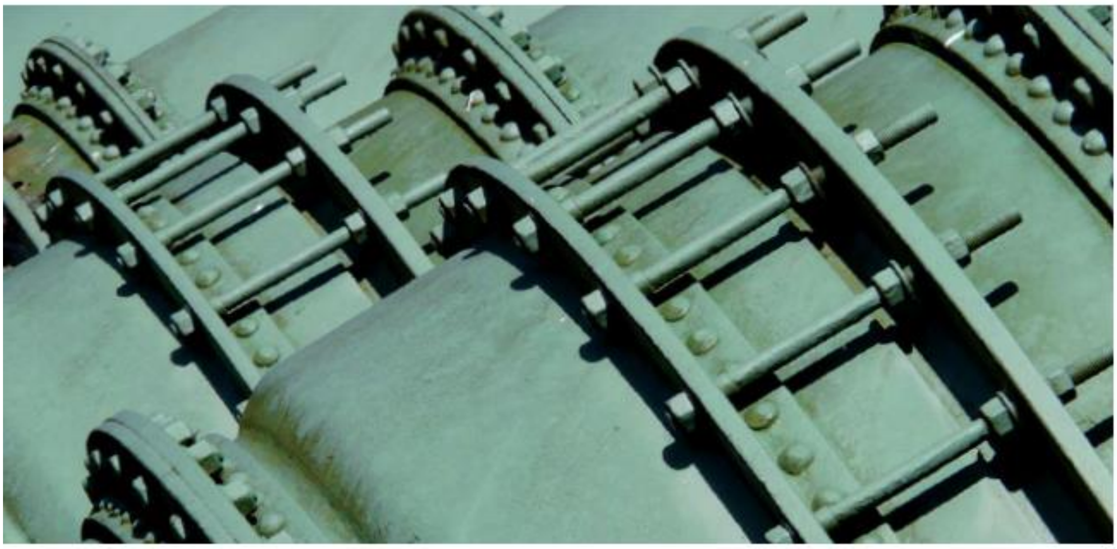
E.1. Article published in the Technical Spanish Magazine of the Environment

REDAWN: reducción de la dependencia energética en redes de distribución de agua mediante micro turbinas

Miguel Crespo Chacón[1], Juan Antonio Rodríguez Díaz[2], Jorge García Morillo[2], Indalecio González Fernández[3]
[1] Trinity College Dublin | www.tcd.ie • [2] Universidad de Córdoba | www.uco.es • [3] Fundación Asturiana de la Energía | www.faen.es

El consumo eléctrico por parte del sector del agua supone aproximadamente un 3,5% del total demandado en la UE, siendo el cuarto sector mayor consumidor dentro de la Zona Atlántica europea. Además, se prevé que esta cifra se incremente en los próximos años, habiéndose estimado que la demanda alcanzará el doble de la actual a nivel mundial en 2040. Esto se traduce en que el sector del agua contribuye significativamente al cambio climático debido a que la mayor parte de la electricidad proviene de combustibles fósiles. Por otro lado, esta dependencia energética encarece los costes de producción y explotación de las diferentes actividades. A estos dos efectos hay que añadirle uno de los principales objetivos del tratado de Paris que consiste en la reducción de la emisión de los gases de efecto invernadero en un 40% para 2030. De los tres motivos expuestos se podría deducir que la industria del agua ha de mejorar su modelo de explotación, centrándose en la mejora de su eficiencia energética.

La energía micro hidráulica se ha presentado como una solución técnica y económicamente atractiva para reducir esta dependencia energética. Dicha tecnología consiste en la instalación de turbinas a pequeña escala, con capacidades de producción que oscilan entre los 5 y los 100kW, que aprovechan el



exceso de presión existente en las redes de agua para la generación de energía eléctrica. Además, la adopción de esta tecnología en redes presurizadas (como pueden ser las redes de abastecimiento, de riego, o para industria) ayudaría a reducir las fugas de la red, que en gran parte se deben a este exceso de presión.

EL PROYECTO

El proyecto REDAWN (Reducción de la Dependencia Energética en Redes de Agua de la Zona Atlántica europea, por sus siglas en inglés) es un proyecto financiando por el programa Interreg Atlantic Area, mediante los fondos para el desarrollo regional europeo. Tiene como principal objetivo el fomento de la tecnología micro hidráulica en general, y de las bombas funcionando como turbinas en particular, para mejorar la eficiencia energética en el sector de la distribución del agua. Dentro del sector del agua, REDAWN estudiará el uso de esta tecnología en redes presurizadas de abastecimiento urbano de aguas, riego e industria. El proyecto nace con la idea de transformar el exceso de presión existente en ciertos puntos de las redes de distribución en energía hidráulica. Actualmente dicha energía no se aprovecha y se disipa a través de válvulas reductoras de presión.

El proyecto está compuesto por 15 socios de seis países que se organizan en ocho paquetes de trabajo. Se trata de una estructura multidisciplinar en la que participan expertos dentro de los diferentes campos de conocimiento que abarcan los objetivos del proyecto y que pertenecen a entidades tales como empresas de explotación de redes de abastecimiento, universidades, organismos públicos, comunidades de regantes, asociaciones de regantes, o industrias. El proyecto está liderado por la empresa Action Renewables con sede en Belfast (Reino Unido). El resto de socios son: Trinity College Dublin (Irlanda), Fundación Asturiana de la Energía (España), Instituto Técnico de Lisboa (Portugal), canal WATEF (Universidad de Bath, Reino Unido), Asociación de comunidades de regantes (FERAGUA, España), Universidad Federico II de Nápoles (Italia), Hidropower (Portugal), Syndicat de Mutualisation de l'eau Potable du Granvillais et de l'Avranchin (SMPGA, Francia), Universidad de Córdoba (España), Renova (Portugal), Portuguese Water Paternship (Portugal), Northern Ireland Water (Reino Unido), Electricidade da Madeira (Portugal) y EDA Renovàveis (Portugal).

Los principales objetivos planteados en el proyecto se centran en el desarrollo de un entorno institucional, social y tecnológico adecuado para fomentar una mayor eficiencia de los recursos disponibles en las redes de distribución de agua. Como tales, han de resaltarse:

Figura 2. Miembros Consorcio REDAWN

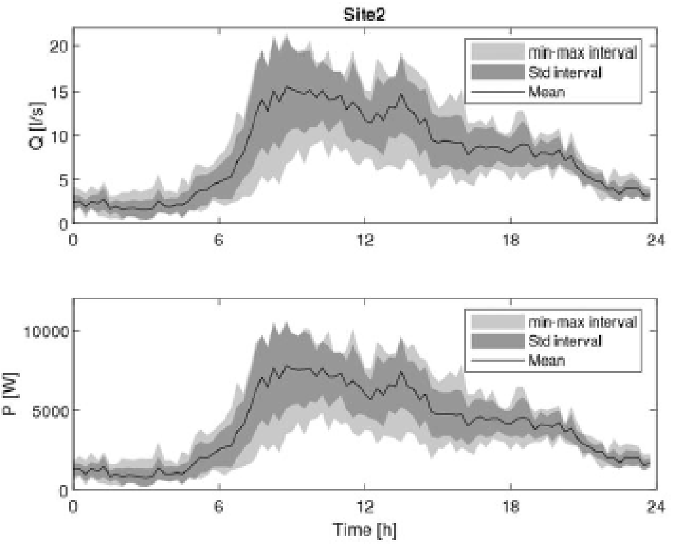
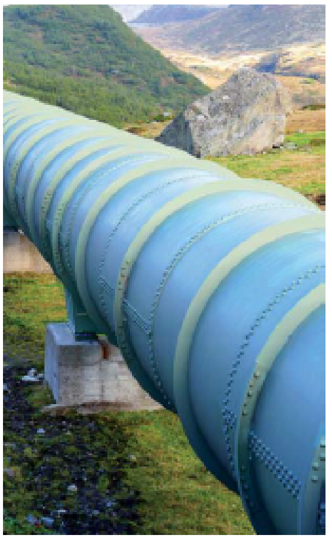


Figura 3. Caracterización de las fluctuaciones de caudal y potencial existente en un caso experimental (Fuente: UNINA)



• Análisis y evaluación del potencial energético disponible, así como el impacto económico y medioambiental de la implementación de esta tecnología en la costa Atlántica europea.
• Desarrollo de unas pautas para el diseño de instalaciones para la generación de energía micro hidráulica mediante el uso de PATs.
• Cuantificación de los impactos sociales.
• Construcción de tres plantas experimentales en tres tipos de instalaciones diferentes (abastecimiento, riego e industria) y difusión de los resultados obtenidos para promocionar una mejora de la eficiencia energética mediante esta tecnología.

TECNOLOGÍA PAT

Las bombas funcionando como turbinas, o PATs por sus siglas en inglés (Pump as Turbines), constituyen una tecnología relativamente antigua, ya que la generación de energía mediante estas empezó a utilizarse alrededor de 1930. Generalmente, suponen una alternativa más económica a las turbinas tradicionales. Esto se debe a la producción en serie de las bombas, que hace que su coste sea aproximadamente una décima parte del de una turbina, cuyo uso no está tan extendido. No obstante, cuentan con la desventaja de una menor eficiencia. Además, esta eficiencia se ve muy afectada por las fluctuaciones del caudal (ver Figura 2), con las que la eficiencia del sistema se ve muy reducida cuando no existe un caudal continuo o cuando no se cuenta con dispositivos de control que permita estabilizar el caudal de alimentación, lo cual afecta a la potencia generada. En el ámbito urbano, estas fluctuaciones pueden ser tanto diarias como estacionales. Por ello, las condiciones de trabajo de las PATs han de ser reguladas de forma externa.

En los últimos años se han desarrollado numerosas investigaciones que estudiaban diversos esquemas y dispositivos para la regulación dichas condiciones. Entre estas estrategias se pueden encontrar la regulación hidráulica y la regulación eléctrica. La regulación hidráulica presenta un esquema en by-pass, mediante el que se pretende regular las condiciones de entrada a la PAT a través de válvulas de control. La PAT funcionaria en paralelo a una válvula reductora de presión, que se encarga de regular la presión de salida del by-pass. Este esquema es muy adecuado en redes donde se encuentren dichas válvulas reductoras previamente instaladas. Por otro lado, encontramos la regulación eléctrica, la cual regula la velocidad de rotación del generador mediante un variador de frecuencia, adaptándose en cada momento a las condiciones existentes en la red.

El uso de válvulas reductoras de presión es muy común en redes de abastecimiento urbano y en redes de riego. En unos casos para la regulación de las fugas que se dan debido a la alta presión existente en las tuberías y a su mal estado de conservación y, en otros casos, para reducir la presión en la acometida del abonado o en el hidrante de riego del agricultor. Por tanto, mediante la instalación de una PAT se conseguirían varios propósitos. Por un lado, la reducción de la presión implica menores pérdidas por fugas en la red y, por otro lado, la generación de electricidad, mediante la cual, y en función de la potencia generada, se podrían alimentar diferentes dispositivos, como pueden ser sensores instalados en la red, sistemas de alumbrado urbano o cargadores de coches eléctricos o, en su defecto, verter a la red y conseguir un pequeño ingreso por la vena de energía.

PLANTAS EXPERIMENTALES

Para poder promocionar el uso de PATs para la recuperación de energía, el proyecto REDAWN tiene dentro de sus objetivos la construcción de tres plantas piloto o experimentales. Las plantas se construirán en tres instalaciones con fines diferentes, una de abastecimiento urbano (Francia), otra de abastecimiento industrial (Portugal) y una de riego (España), que se construirá en la Comunidad de Regantes del canal de la margen izquierda del Genil, en Palma del Rio (Córdoba).

La planta que se va a instalar en la red de riego se realizará en las instalaciones de un regante con una explotación de almendros. Su objetivo es aprovechar el exceso de presión existente en un hidrante (mínimo de 20 mca) para la generación de energía eléctrica. Con la electricidad generada se sustituirá un generador diésel que se utiliza para alimentar a un sistema de filtrado, dos bombas inyectoras de fertilizante y un compresor. Debido a la estacionalidad de la actividad, el consumo de diésel aumenta significativamente en los meses centrales del año, en los que los cultivos tienen mayores necesidades hídricas, siendo prácticamente nulo en los que no hay riego.

Además, la instalación contará con un pequeño almacenamiento energético en baterías para cubrir los picos de demanda y por si existen consumos eléctricos cuando se realicen labores de mantenimiento de la microturbina. La PAT tendrá una potencia nominal de 4kW con un panel eléctrico de inversores trifásicos de 9 kW de potencia nominal y 18 kW de potencia pico. En los momentos en los que la instalación demanda más de los 4 kW generados por la PAT, el resto de energía lo aportan el banco de baterías. En momentos en los que se consume menos y las baterías se encuentran cargadas, la microturbina se autorregula para generar sólo lo que demanda la instalación. Además, dado que la instalación se encuentra en una zona con alta radiación solar, con unos valores de radiación diaria media que varían de 5 a 7,5 hsp en épocas de riego, se complementará la PAT con 2 placas solares de 330Wp, para que en periodos donde no se requiere riego y, por tanto, no funcione la PAT, el banco de baterías siempre esté cargado y el sistema de monitorización funcione.

Los beneficios potenciales de la planta piloto son bastante claros. En el ámbito medioambiental, habrá una notable mejoría evitando la emisión de gases de efecto invernadero producidos por el generador diésel y reduciendo, de este modo, su huella de carbono asociada. En la parte económica, el regante aprovechara el exceso de presión existente para alimentar la estación de fertirriego, ahorrándose la compra de diésel que, por otro lado, es un combustible cuyo precio está previsto que siga aumentando en los próximos años.

Los resultados y beneficios obtenidos en cada una de las plantas, al igual que las diferentes investigaciones que se llevaran a cabo en el proyecto, serán difundidos a través de hojas informativas, congresos, revistas técnicas, científicas y a través de la web del proyecto (www.redawn.eu) y las webs de sus participantes, para así dar a conocer la problemática existente y a la vez promover soluciones innovadoras orientadas a reducir la dependencia energética de las empresas que gestionan las redes de distribución de agua con distintos fines.

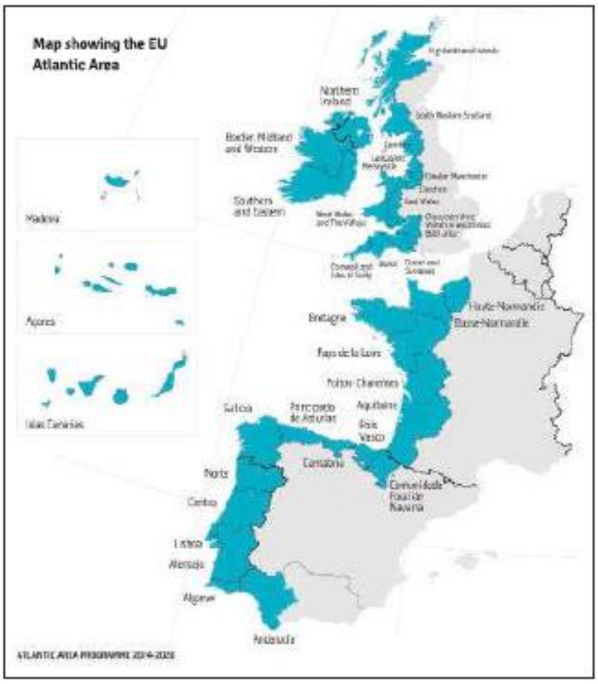
Figura 4. Vista aérea de la Comunidad de Regantes del canal de la margen izquierda del Genil

Figuras 5-6. Diseño de la planta experimental en la red de riego (Fuente: Tecnoturbines)

E.2. Article published at the International Water Power and Dam Construction Magazine

The REDAWN of micro hydropower

A European funded project is exploring the water-energy-food nexus and is proposing viable solutions to convert these diverse challenges into positive social, economic and environmental opportunities



THE EU WATER SECTOR utilises about 3.5% of the total energy demand. From the current global trend, energy use in the sector will almost double by 2040. This makes the water sector a significant contributor to climate change, due to the fossil fuel sources used for the energy production. The transition to renewable energy sources will help to alleviate this impact and achieve the Paris Agreement ambition of 40% reduction in greenhouse gases (GHG) by 2030.

Micro hydropower (MHP) refers to a technique of using turbines situated within water channels or pipes to generate power of between 5-100kW. Its technical application takes advantage of the existing flow and excess pressure within the network to generate electricity. Using this technology in pressurised water networks (drinking water, industry, irrigation or wastewater) could lead to important benefits, such as the improvement in energy efficiency, pressure and leakage management. Social and economic benefits are also accruable such as reduction in operation and maintenance costs for providers on one hand, and reducing water and energy poverty, especially in remotes areas, on the other.

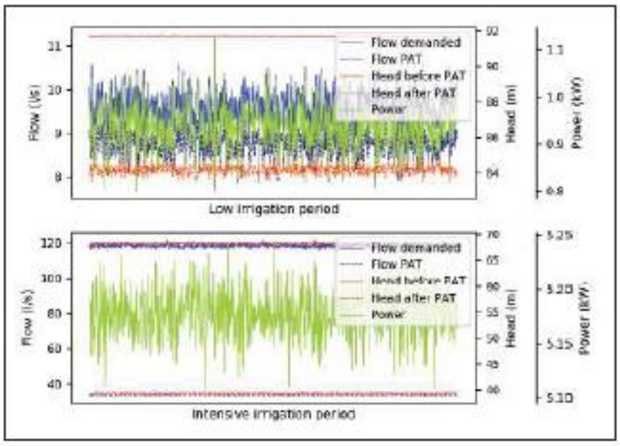
The REDAWN Project

The REDAWN Project (Reducing the Energy Dependency in Atlantic Area Water Networks) is a project partially funded by the Interreg Atlantic Area program through the European Regional Development Fund. The project was born with the idea of recovering the existing excess pressure at key points in water networks, which is typically dissipated with devices, such as pressure reducing valves. The multidisciplinary project team, whose contribution are organised in eight work packages (www.redawn.eu/work-packages) comprises nine main partners from six European countries. The consortium includes academic, industry and public organisations.

The aim is to promote the use of MHPs with pumps-as-turbine (PAT) to produce renewable energy, thereby improving the energy efficiency of the water sector. The project also seeks to understand the contextual, environmental and institutional opportunities and constraints to the uptake of MHPs in the EU's Atlantic Area. Therefore, the study encompasses different water-using sectors such as municipal water supply, water for irrigation as well as process industry water/waste water systems to deliver the following objectives:

Left: **The REDAWN team at the demonstration plant on a farm in Andalusia, Spain**

- Produce an energy recovery resource, economic and environmental impact assessment of MHPs in Atlantic Area water networks (https://www.redawn.eu/mapping-potential-energy-recovery-atlantic-area).
- Develop design guidelines and support tools for hydropower energy recovery in drinking water, wastewater, irrigation and process industry sectors.
- Develop policy and institutional support tools to increase the implementation of energy recovery projects.
- Quantify the societal impacts of hydropower energy recovery in water networks.
- Construct three pilot demonstration plants for three different water sectors, such as drinking water, process industry and irrigation.
- Widespread dissemination of the results obtained and promotion of energy efficiency in Atlantic Area water networks.



The novelty is PAT

The technical basis of the REDAWN project is pumps working in reverse, or Pump-as-Turbines (PATs). Compared to traditional turbines, PATS have been shown to be an attractive, cost-effective solution for small hydropower plants. We have found that they can be 90% cheaper than conventional MHP turbines. They are also mass produced and readily available in the market. PATs could be used to exploit the existing excess pressure in some points of the network and recover this energy for different purposes. However, PATs have the disadvantages of a lower efficiency, which drop significantly with high flow fluctuations affecting to the power production. Thus, control elements are often required to regulate their working conditions and we are also proposing solutions to address this challenge.

There have been several studies on how these conditions can be regulated and the most well-known approaches are the hydraulic and the electric regulation. The electric regulation is based on the control of the rotational speed of the device using variable speed drives, to adjust the speed to the conditions of the network. The hydraulic regulation approach uses a bypass configuration combined with hydraulic devices (e.g. pressure reducing valves) to control the working conditions whilst minimising disruption. Other useful technical information can be found here: https://www.redawn.eu/publications.

Demonstration sites

Demonstration sites are very useful for showcasing innovation, providing the basis for comparison and to test and refine technologies. Therefore, this project proposes three demonstration sites in the Atlantic Areas of Spain (irrigation), France (municipal/public water) and Portugal (process industry).

The Spanish pilot plant within pressurised irrigation network located in Andalusia was used during the entire 2019 irrigation season supplying irrigation and fertilisation for about 300 hectares of farmland. The plant, consisted of a hybrid solution of two back-up solar panels of 600W, a 4kW PAT and a set of four batteries. The solar panels were used in periods out of the irrigation season to maintain the optimum level of the batteries. The PAT was used to replace the diesel

Top: **Flow and head fluctuations characterisation for a pressurised irrigation network and theoretical power production depending on the irrigation stage**

Above: **Diagrammatic representation of a hydraulic by-pass configuration for micro hydropower**

Left: **The REDAWN pilot plant constructed in the irrigation sector, which worked for the 2019 irrigation season**

Above: **A paper manufacturing plant in Portugal will be used as a demonstration for the process industry**

economic benefits have been achieved, completely avoiding greenhouse gases emissions and all the direct and indirect diesel generator costs. This is in addition to branding, marketing and productivity value for the farm because of the renewable energy system.

Two sites are proposed in France: the first to be installed in SMPGA's drinking water distribution network in Normandy. The data and results obtained from this plant will be very interesting, due to the significant renewable energy opportunities in municipal water networks, including for pressure and leakage management.

The second installation is a free mobile-phone charging point near a well-used bus-stop to raise awareness of the technology and to highlight its multifaceted social benefits where such facilities, e.g. electric car charging points, would otherwise be difficult or costly.

The demonstration for the process industry will be installed in a paper factory in Portugal. Industries like dairy, alcohol, mining and paper utilise a lot of water during manufacturing processes and are always looking for ways to be both water and energy efficient. The current supply infrastructure in this site consists on an open channel flow, which will be pressurised, and the water channelled through a 10 kW PAT. Green energy points are accruable by the company and the resulting energy will be reused on site.

Energy efficient

Population growth, increasing industrialisation coupled with the rising demand for food, water and energy makes resource use sustainability and resilience essential. The economic viability of most sectors – with direct links to jobs, livelihoods and wellbeing – necessitates efficient practices as well as the use of renewable energy sources. The REDAWN project explores this vital water-energy-food nexus and proposes viable solutions to convert these diverse challenges into positive social, economic and environmental opportunities.

Our results so far are being disseminated in industry magazines and forums, scientific journals, international conferences and other important events, such as international technical fairs. We have also developed a training course, regularly organise dedicated events and webinars with our partners.

A more energy efficient water sector is possible. ●

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More information
Visit the website **www.redawn.eu** join the mailing lists or attend any of the events to find out more