Jul 5th, 12:00 AM - Jul 8th, 12:00 AM

Estimation of the Efficiency of Hydraulic Pumps

A. Martin-Candilejo
Universidad Politécnica de Madrid, araceli.martin@upm.es

D. Santillán
Universidad Politécnica de Madrid

L. Garrote
Universidad Politécnica de Madrid

Estimation of the Efficiency of Hydraulic Pumps

A. Martin-Candilejo[1], D. Santillán[1] and L. Garrote[1]
[1]Escuela Técnica Superior de Ingenieros de Caminos, Canales y Puertos of Madrid,
Departamento de Ingeniería Civil, Hidráulica, Energía y Medio Ambiente
Universidad Politécnica de Madrid
Profesor Aranguren 28040
SPAIN
E-mail: araceli.martin@upm.es

Abstract: *A sustainable design of water supply systems needs to account operational costs. When pumping is required, the energy consumed by the pumps plays a major part in the operational costs, and the efficiency of the pumps can greatly affect the energy expenses. How to properly estimate the value of pump efficiency is hence of great importance. The aim of this study is to study in depth the efficiency of hydraulic pumps, in relation with the other design variables (flow rate, pumping head, power, etc.). For that, 400 hydraulic pumps were analysed. A strong relationship between the flow rate and the pump efficiency was observed. This relationship was interpolated, and three empiric curves were defined (one for the average maximum and minimum expected value of pump efficiency). These curves can be easily used by designers in order to obtain an estimation of the efficiency of the hydraulic pumps.*

Keywords: *pump efficiency, water supply systems, design optimization, hydraulic pumps.*

1. INTRODUCTION

Under the threat of climate change, becoming energy efficient is of increasingly importance. In order to be more sustainable, the designing of a water supply system needs to consider both construction costs and operational costs, along its entire lifespan. When the facility requires pumping, investing little in construction costs will result in a much higher energy requirement. Therefore, addressing the operational expenses from the design stage is the sustainable approach.

Mala-Jetmarova et al (2018) well summarizes the different approaches to optimise the design of water supply systems. These approaches can be differentiated in single objective (e.g., Martin-Candilejo, 2020; Dziedzic et al 2015; Joong Hoon Kim & Mays, 1994; Sanchis et al 2019; Samani & Mottaghi, 2006; Kang et al 2013; Spiliotis & Tsakiris, 2007; or Costa et al 2000) or multi objective techniques (e.g., Vamvakeridou-Lyroudia et al 2005; Jin et al (2008). Either way, the most frequent objective is cost minimisation. In order to achieve a more precise assessment of all costs involved, multi-objective algorithms have started to incorporate in the optimization function costs of maintenance (Perelman & Ostfeld, 2007; Perelman et al 2008), greenhouse gas emissions (Wu et al 2010), among others. Multi-objective methods offer a very complete analysis of all costs, but many times they require very complex programming, resulting in computationally expensive and hard to use. That is the reason why single objective (cost optimization) remain as the most used approach in the practical scenario. Reed et al (2013) explains extensively the state-of-art of the multi-objective techniques. The most popular of these rely on iterative algorithms, such as genetic algorithm.

In any case, if a complete cost optimization (this includes operational expenses) is to be carried out, the estimation of the pump's efficiency μB is required, no matter the algorithm or the methodology of the optimisation. The value of the hydraulic pump efficiency has been typically estimated based on the experience of the designer; for instance, some of the most cited authors have made the following estimations: Alperovits & Shamir, (1977) estimated μB at 75%, and so did later Featherstone & El-Jumaily, (1983), Gessler & Walski, (1985) and Kapelan et al (2005); some more recent authors are Filion et al (2007) whose estimation is an interval between 81-84%. The energy cost is directly (inversely) proportional to μB. Hence the importance of a proper estimation of the pump efficiency Martin-Candilejo, et al (2020). This research analysed the values of the pump efficiency in order to provide designers some guidelines on how to choose the estimated value of µB.

2. METHODOLOGY

The aim of this research is to analyse the relationship of the pump efficiency and the other design parameters of a water supply system, such as the flow rate, the pumping head or the required power. For this task, a sample of 400 commercial hydraulic pumps was selected (Martin-Candilejo et al 2020). These pumps come from catalogues of different manufactures. These manufactures were IDEAL, WILO, ESPA and HASA. More specifically, the commercial models were:

- Split case pumps: CP/CPI/ CPR series.
- Horizontal pumps (normalized in the European Union): RNI/RN series.
- Multistage horizontal pumps: APM series.
- Vertical pumps: VS/VG series.
- Submersible vertical pumps: SVA/SVH series.

We discarded custom made pumps, and also those pumps for industrial or sanitary uses, since they have particular specifications, and the study focused on water supply pumps. In the end the sample consisted of 226 hydraulic pumps. All of the pumps differ from each other in their type, impeller, diameter, number of stages, rotation speed (electrical current frequency, number of poles), brand, etc. In the case of multistage pumps, for each flow rate, no matter the number of stages, they perform with the same efficiency. To avoid repetition and dispersion, it was decided only to use the operating point of a single stage. The data should be updated and completed in the fore coming years to fill in any bias and include more manufactures.

When the pumping station is designed, the pumps are chosen to best perform at the estimated operational point. This is the estimated flow rate and pumping head. Hence, the pumps are chosen so that this operating point is the closest to the optimum point of the pump, that is the point at which the pump will perform at its best efficiency. It is true that later in the operation, the pumps will vary the operating point according to the variable demand of water. But at the design stage, what interests the most is the optimum point (Martin-Candilejo et al 2021). For this reason, we registered the optimum value of the pump efficiency, with its correspondent flow rate, head, power consumption, frequency and speed. It should be clarified that this value of the pump efficiency μB refers to the hydraulic efficiency and does not include mechanical or electrical losses. With this collected data the study was carried out to analyze the variations of μB and the other design variables.

3. RESULTS AND DISCUSSION

3.1. Pump Efficiency and Flow Rate

The pump efficiency was first plotted against the flow rate in Figure 1. As it can be seen, a strong correlation can be observed. The minimum values of the optimum pump efficiency correspond to the smallest flow rates, somewhere over 65%. However, it soon starts to grow, and by 300 l/s, the pump efficiency has already reached a value of 85%. The curve continues to grow towards an asymptotic value of no more than 90%.

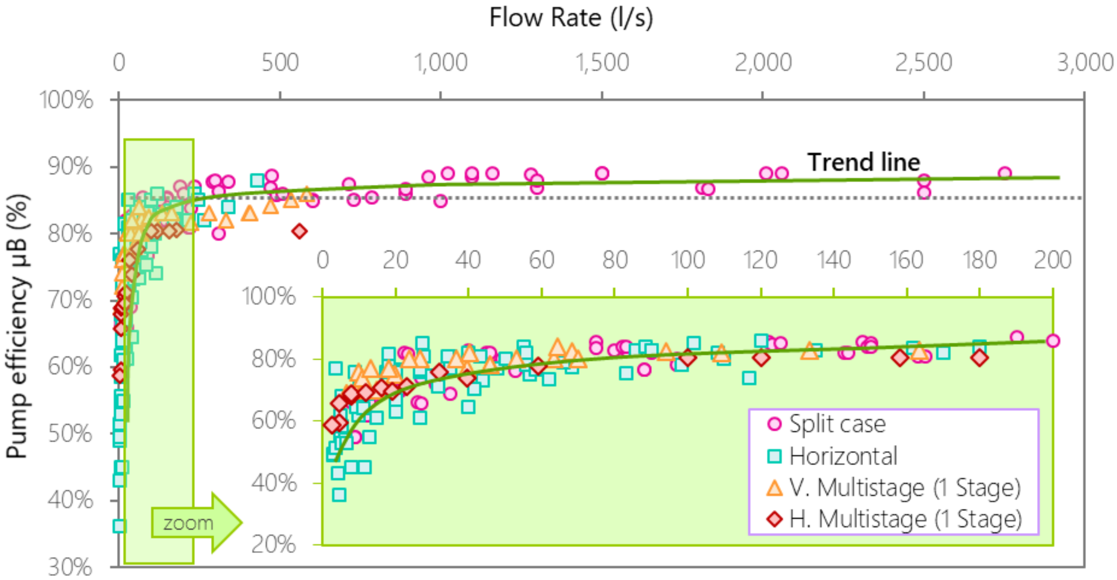

Figure 1 - Relationship between the flow rate and the pump efficiency.

Regarding the influence of the type of pump, split case pumps are the ones that are capable to work with the highest flow rates, and therefore, they are also correspondent to the highest pump efficiency. They are the predominant type for over 400 l/s and 85%. The rest of the regular horizontal pumps work for much smaller flow rates (under 250 l/s) and thus, lower values of the pump efficiency. Vertical and horizontal multistage pumps work in the same spectrum of flow rates (also under 250 l/s), but over all the vertical multistage pumps perform better for any flow rate than the horizontal multistage pumps. It should also be clarified that submersible vertical pumps are included in the vertical multistage category, since they were very few.

3.2. Pump Efficiency and Pumping Head

When the optimum pump efficiency is plotted against the pumping head in Figure 2, no relationship can be seen. The distribution of dots is too scattered to withdraw any conclusions. Therefore, it can be said that there is no relationship between the optimum pump efficiency and the pumping head.

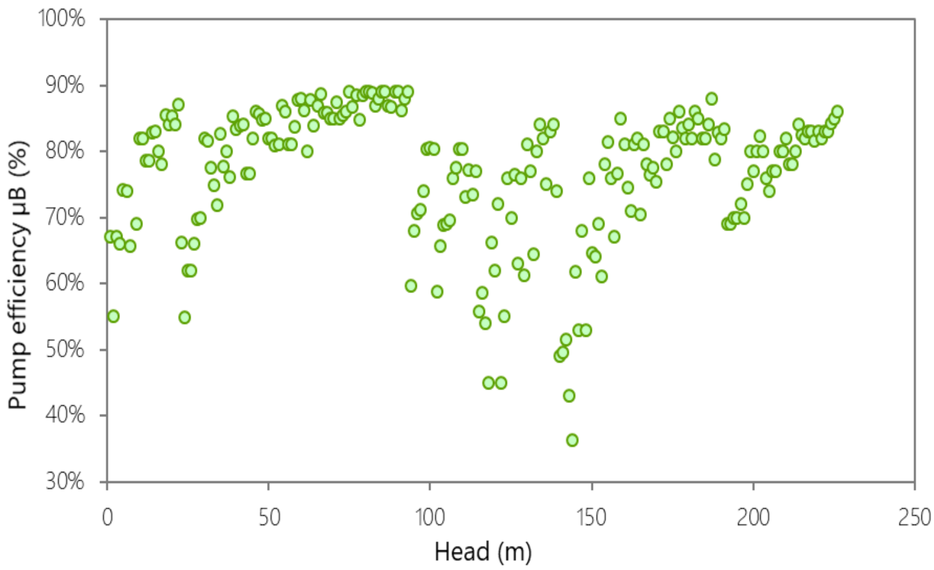

Figure 2 - Relationship between the pumping head and the pump efficiency.

3.3. Pump Efficiency and Power

The results for the relationship between the pump efficiency and the pumping power are very similar to those obtained with the flow rate: a clear relationship is observed in Figure 3. However, in this case the relationship is weaker since the distribution presents more dispersion. Nevertheless, the shape is very similar: it is a growing curve with an asymptote at almost 90%. For over 250 kWh, the pump efficiency can be expected to be higher than 85%. The reason of this slightly bigger dispersion can be explained by the fact that the pumping power is obtained from the flow rate, but also from the pumping head. The poor relationship between the pumping head and the pump efficiency could be responsible for the dispersion. Nevertheless, it can be concluded that there is a relationship between the pump efficiency and the power.

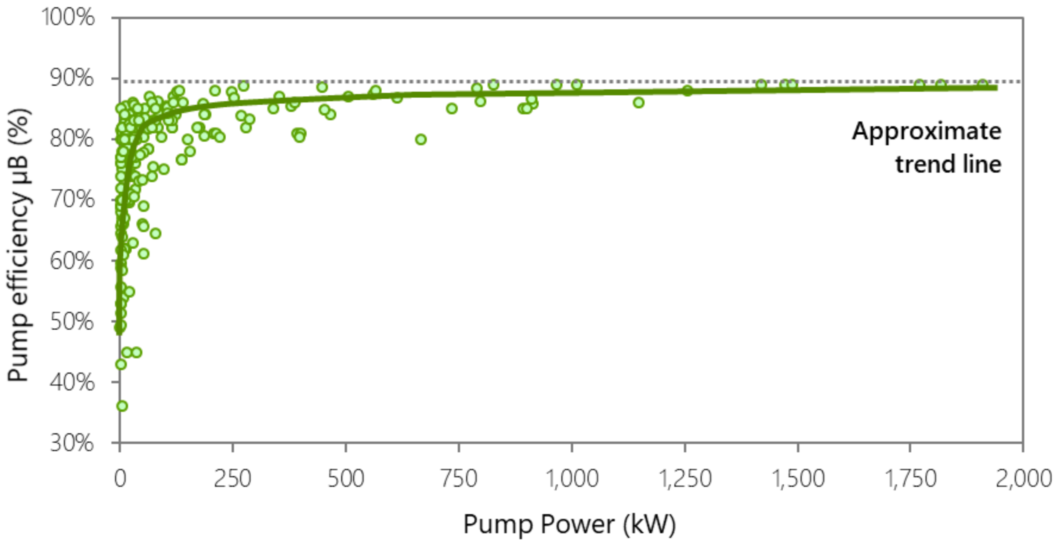

Figure 3 - Relationship between the pumping power and the pump efficiency.

3.4. Pump Efficiency and Speed.

It was also studied the relationship between the pump efficiency and the rotation speed (see Figure 4), the specific speed. The rotation speed of the pump is a discrete variable that depends on the frequency of the electrical network and the number of poles. The most common values are 1450 rpm and 2900 rpm. In either case, all range of values of the pump efficiency could be found. Therefore, no relationship between the pump efficiency and the rotation speed can be concluded.

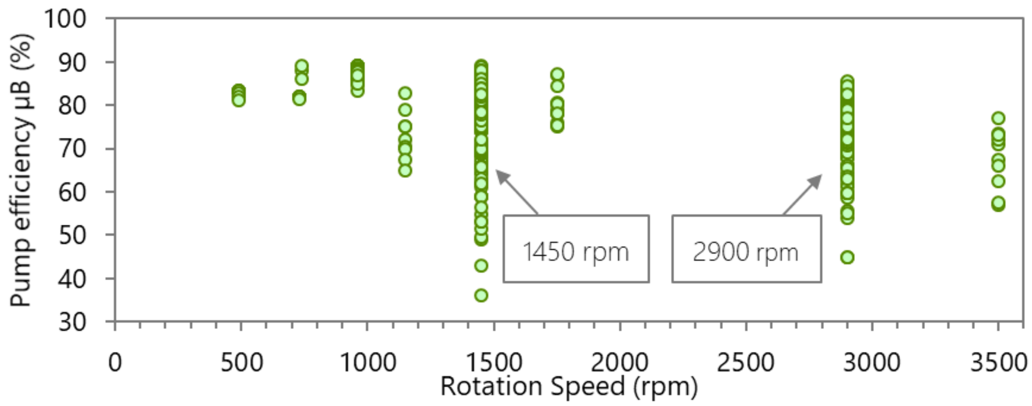

Figure 4 - Relationship between the rotation speed and the pump efficiency.

The specific speed is interpreted as the rotation speed that a homologous pump should have in order to elevate a discharge of 1 m^3/s at 1m height Martin-Candilejo,et al., (2020). The vast majority of the pumps showed a specific speed of 5-80 rpm. In that interval, the pump efficiency was also increasingly growing (see Figure 5), in a similar way as the flow rate or the power did; nevertheless, much more dispersion was observed. Thus, no sufficiently clear relationship was concluded.

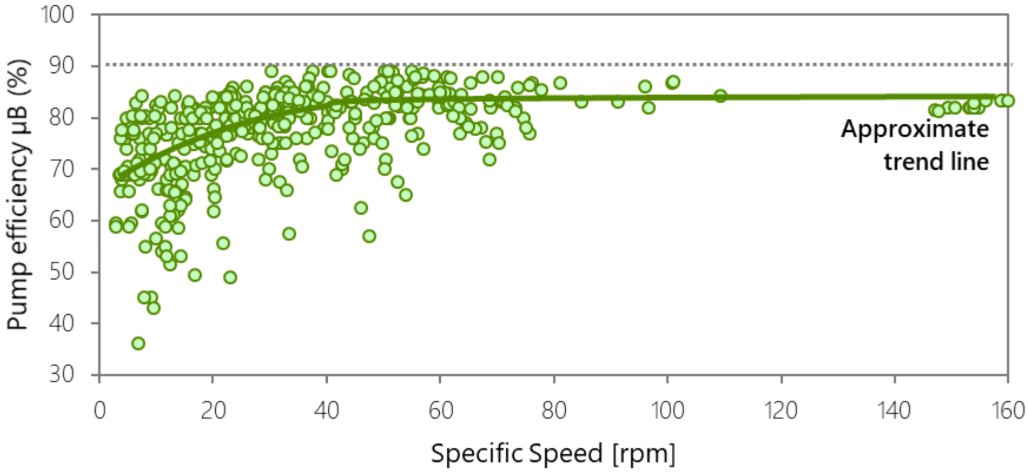

Figure 5 – Relationship between the pumping power and specific speed.

3.5. Average Pump Efficiency Depending on the Pump Type.

Overall, all the possible values of the pump efficiency can be seen in Figure 6, organised by the pump type. The average value is also marked for each type. It can be seen that in average, the split case is the type that offers the highest average values, and horizontal pumps are the ones that offers a wider range of pump efficiency. Once again, vertical multistage show better results than horizontal multistage.

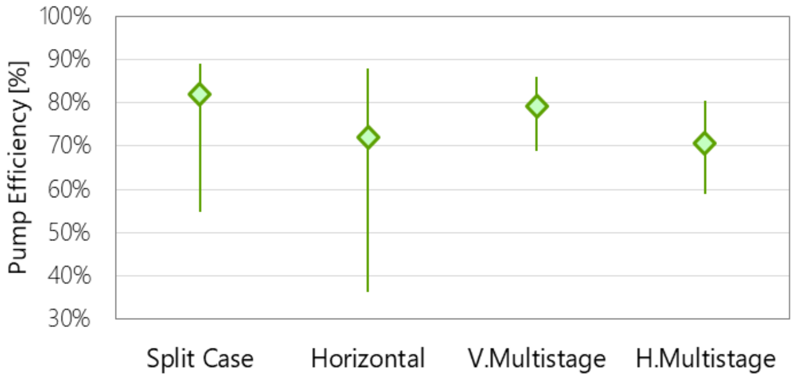

Figure 6 - Pump efficiency range and average values depending on the pump type.

3.6. Definition of the Relationship of the Pump Efficiency and Flow Rate.

Since the relationship between the optimum pump efficiency and the flow rate was the strongest observed, it was decided to properly define an interpolated empiric curve that could serve to estimate μ_B, from the design flow rate. The interpolation was carried out for the average and the maximum expected value of μB. The curve was fitted by sectioning the data in 14 sections. The values of each section were adjusted through a doubly logarithmic curve, and the curve fit very satisfactory. The curves can be seen in Figure 7. The empirical equations of the relationship between the flow rate and the expected optimum values of the pump efficiency are:

$$Average\ \mu B \rightarrow \mu B = 0.1286 \cdot \ln(2.047 \cdot \ln(q) - 1.7951) + 0.5471 \qquad r^2>98\% \qquad (1)$$
$$Maximum\ \mu B \rightarrow \mu B = 0.0576 \cdot \ln(2.047 \cdot \ln(q) - 1.7951) + 0.741 \qquad r^2>90\% \qquad (2)$$
$$Minimum\ \mu B \rightarrow \mu B = 0.2074 \cdot \ln(2.047 \cdot \ln(q) - 1.7951) + 0.3161 \qquad r^2>95\% \qquad (3)$$

where *q* the flow rate in litres per second (l/s).

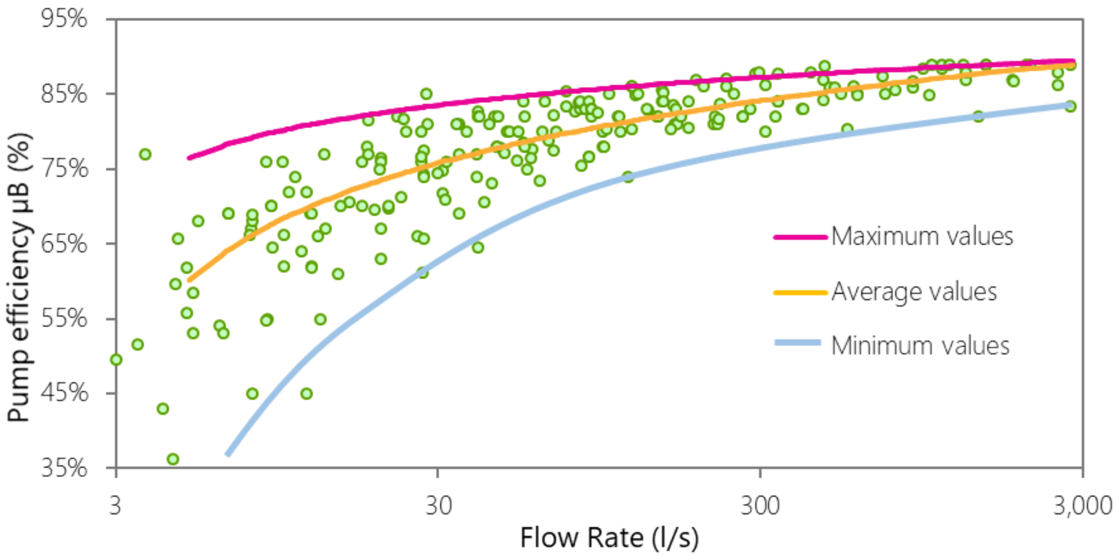

Figure 7 - Fitted curves of the flow rate and the pump efficiency.

4. CONCLUSION

The efficiency of the hydraulic pumps was analysed in depth, in relation with the other design variables. A relationship between the pump efficiency and flow rate or the pumping power was observed. Any relationship with the pumping head or the rotation speed was discarded. A slight relation with the specific speed was observed.

Since the relationship between the flow rate and the pump efficiency is very strong, an interpolated curve was fitted. This curve can be easily used by designers to estimate the value of the pump efficiency in the design of a water supply system that requires pumping. The curves only provide an orientate value of the hydraulic efficiency. The final value would depend on the pump selected by the designer. Entering with the design flow rate, the curve immediately returns the value of the estimated average or maximum optimum pump efficiency. Say that the supply system required a design flow rate of 300 l/s; the practitioner would enter the curves and see that the expected average value of the hydraulic efficiency of the pump would be 80% and the maximum that efficiency that could be found in the marked is around 85%. These empiric curves can be a great resource to properly incorporate the costs of pumping in the design of a water supply system. These results can be applied for the design stages of a water supply system, for instance, in agricultural purposes or in urban areas.

5. ACKNOWLEDGMENTS

This work was funded by Fundación Carlos Gonzalez Cruz; to whom we are deeply grateful.

6. REFERENCES

Alperovits, E. and Shamir, A. U. (1977) *Design of Optimal Water Distribution Systems*, Water Resources Research.

Costa, A. L. H., Medeiros, J. L. D. and Pessoa, F. L. P. (2000) *Optimization of pipe networks including pumps by simulated annealing*, Brazilian Journal of Chemical Engineering, 17.

Dziedzic, R., Karney, B. W. and Asce, M. (2015) *Cost Gradient-Based Assessment and Design Improvement Technique for Water Distribution Networks with Varying Loads*, Journal of Water Resources Planning and Management, 142(1).

Featherstone, R. E. and El-Jumaily, K. K. (1983) *Optimal Diameter Selection for Pipe Networks*, Journal of Hydraulic Engineering, 109(2), pp. 221–234.

Filion, Y. R., Adams, B. J. and Karney, B. W. (2007) *Stochastic Design of Water Distribution Systems with Expected Annual Damages*, Journal of Water Resources Planning and Management, 133(3), pp. 244–252.

Gessler, J. and Walski, T. (1985) *Water Distribution System Optimization.*

Jin, X., Zhang, J. and Gao, J. (2008) *Multi-objective optimization of water supply network rehabilitation with non-dominated sorting Genetic Algorithm-II*, Journal of Zhejiang University-Science A, 9(3), pp. 391–400.

Joong Hoon Kim, B. and Mays, L. W. (1994) *Optimal Rehabilitation Model for Water-Distribution Systems*, Journal of Water Resources Planning and Management, 120(5).

Kang, D., and Lansey, K. (2013) *Scenario-Based Robust Optimization of Regional Water and Wastewater Infrastructure*, Journal of Water Resources Planning and Management, 139(3), pp. 325–338.

Kapelan, Z. S., Savic, D. A. and Walters, G. A. (2005) *Multiobjective design of water distribution systems under uncertainty*, Water Resources Research, 41(11), pp. 1–15.

Mala-Jetmarova, H., Sultanova, N. and Savic, D. (2018) *Lost in optimisation of water distribution systems? A literature review of system design*, Water (Switzerland). doi: 10.3390/w10030307.

Martin-Candilejo, A., Santillán, D., Iglesias, A., and Garrote, L. (2020) *Optimization of the design of water distribution systems for variable pumping flow rates*, Water (Switzerland), 12(2), pp. 1–19.

Martin-Candilejo, A., Martin-Carrasco, F. J. and Santillán, D. (2021) *How to Select the Number of Active Pumps during the Operation of a Pumping Station: The Convex Hyperbola Charts*, Water, 13(11), p. 1474.

Martin-Candilejo, A., Santillán, D. and Garrote, L. (2020) *Pump efficiency analysis for proper energy assessment in optimization of water supply systems*, Water (Switzerland), 12(1).

Perelman, L. and Ostfeld, A. (2007) *An adaptive heuristic cross-entropy algorithm for optimal design of water distribution systems*, Engineering Optimization, 39(4), pp. 413–428.

Perelman, L., Ostfeld, A. and Salomons, E. (2008) *Cross Entropy multiobjective optimization for water distribution systems design*, Wiley Online Library, 44(9), p. 9413.

Reed, P. M. *et al.* (2013) *Evolutionary multiobjective optimization in water resources: The past, present, and future*, Advances in water resources, pp. 97–103.

Samani, H. M. V. and Mottaghi, A. (2006) *Optimization of Water Distribution Networks Using Integer Linear Programming*, Journal of Hydraulic Engineering, 132(5), pp. 501–509.

Sanchis, R. *et al.* (2019) *Solution approaches for the management of the water resources in irrigation water systems with fuzzy costs*, Water (Switzerland), 11(12).

Spiliotis, M. and Tsakiris, G. (2007) *Minimum Cost Irrigation Network Design Using Interactive Fuzzy Integer Programming*, Journal of Irrigation and Drainage Engineering, 133(3), pp. 242–248.

Vamvakeridou-Lyroudia, L. S., Walters, G. A. and Savic, D. A. (2005) *Fuzzy Multiobjective Optimization of Water Distribution Networks*, Journal of Water Resources Planning and Management, 131(6), pp. 467–476.

Wu, W., Simpson, A. R. and Maier, H. R. (2010) *Accounting for Greenhouse Gas Emissions in Multiobjective Genetic Algorithm Optimization of Water Distribution Systems*, Journal of Water Resources Planning and Management, 136(2), pp. 146–155.