COST OPTIMIZATION OF LOOPED NETWORKS WITH MULTIPLE PUMPING WATER SOURCES

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ABSTRACT

The cost of pumping is one of the most significant operational expenditures in a water distribution network. When a network has multiple water sources, which are associated to pumping stations, it may be possible to optimize those costs. One way to minimize costs is to determine the optimal flow rate for each pumping station and for every point of the temporal demand curve, while keeping the energy cost minimized. This also requires that the required minimum pressure at the critical point in the network to be satisfied. This paper introduces the principle known as the setpoint curve as the key component of the network optimization methodology. A direct search algorithm based on Hooke-Jeeves approach has been tested on two case studies. Two key cost factors, the electric tariff and the cost of water production have been considered for each water supply source. The model also considers the pressure dependent consumption, which directly influences the setpoint curve. To test the methodology, a software application has been implemented using the EPANET toolkit. The two case studies demonstrate the benefits of the approach in developing optimal pump operating policies, which would otherwise be difficult to infer.

Keywords: water, energy, pressure, optimization, network, costs

INTRODUCTION

The two main types of costs associated with managing water distribution networks are capital (CAPEX) and operational expenditure (OPEX). Those costs can increase significantly in the future if new water resources are required or water management efficiency has to be implemented to mitigate against impact of demand increases. This in turn can significantly increase pressure on water utility budgets, thus requiring all costs to be evaluated and optimized. In networks containing pumps, capital costs may increase if a new pumping station is required, but also operational costs can be affected mainly because system pressure must be readjusted. As pumping energy represents a major OPEX cost, improved pump control must be considered as a priority when a more efficient network operation is sought (Jowitt & Germanopoulos 1992). Therefore, optimal operating conditions must be established for each pumping station and the system overall. If that is done correctly, no new pumping stations may be needed even when additional demand is encountered in the system. Optimal pumping operation then leads to reduction the overall energy cost. It is well known that pump flow rate and pressure head determine the amount of energy used by a pump. Therefore, the basic question is what are the minimum flow rate and pumping head required to satisfy the flow and minimum pressure requirements in the network (i.e., at each demand node). Thus, this paper focuses on improving operations of a water distribution network by minimising energy costs of pumping.

For some time the emphasis has been on the need to develop more comprehensive analysis and optimization tools for water networks to improve their efficiency and acceptance (Goulter 1992). To date, much of that effort has been invested in optimizing pumping in water networks. Ormsbee & Lansey (1994) presented an overview of pump scheduling where different approaches are analysed depending on the hydraulic network, demand forecast and optimal control models. With regard to optimization models, it has been pointed out that energy-consumption costs may be reduced by: decreasing either the quantity of water pumped or the total system head; by increasing pumping efficiency by proper pump or pump combination selection; by using tanks to achieve high efficiency in pump operations; or by shifting pump operation to off-peak demand periods controlling storage levels and energy costs. Furthermore, when pump maintenance costs are taken into account as a part of operational considerations, optimization will attempt to minimize the number of pump switches.

Fundamentally, optimization methods (linear programming, dynamic programming, or nolinear programming) are mathematical models used to find the optimal values of some decision variables. In pump control problems, the decision variables may be represented either directly or indirectly. In the former case, a decision variable is expressed as the fraction of time that the pump is operating over a time interval. Therefore, the objective is to minimize the energy cost associated with the operation of each pump for each interval. In the latter case, a decision variable is expressed in terms of a substitute variable, such as a tank level or pump station discharge. This means that the aim is to find the least-cost tank level trajectory or the least-cost time distribution of pump flows (or heads). Then that solution needs to be converted to a pump operation policy. Both approaches have been used in the past to develop methodologies for optimizing different pumping systems, i.e., those with single- or multiple-pumping stations with no tanks, those with a single tank with single- and/or multiple-pump stations, and those with multiple-tank and multiple-source systems. However, these methodologies have been developed under the limitations of computational efficiency encountered at that time of their development. As the computational resources advanced over time, the number of state and decision variables has increased and new algorithms have been developed, such the harmony search, genetic algorithms, ant-colony optimisation, and others (López-Ibáñez et al. 2008; Błaszczyk et al. 2010; Henrique et al. 2015). Later studies have included the multi-objective criteria in the search for the optimal pumping schedules. However, the inclusion of more objectives are making the problem more complex and in some cases, they are unnecessary. On the other hand, most previous methods were based on the use of fixed speed pumps, which have as a major disadvantage that they produce pressures in a water distribution system that are significantly higher than required and could exceed specifications (Lingireddy & Wood 1998). In those situations, hydraulic efficiency of keeping pressures low (and consequently leakage) in the network is not addressed.

To improve hydraulic performance, the pump system efficiency curves should be adapted to be as close as possible to the system characteristic curve (discharge and pressure head required by the network), (Planells Alandi et al. 2005; Lamaddalena & Khila 2012). Therefore, the use of variable-speed pumps can alleviate that problem and provide hydraulic and economic benefits by reaching a high efficiency, as demonstrated by Lamaddalena & Khila (2013). In the same way, Viholainen et al. (2013) formulated a new control strategy for variable speed-controlled parallel pumps taking into account the relation between the preferable operating area (POA) and pump energy efficiency to reach a high performance level. However, all these studies are based on the system characteristic curve (resistance curve), which is usually difficult to determine in drinking water distributions networks as it depends on the demand variations both in time and space.

It should be noted that most of the optimization models start with pre-selected pumps, meaning that once the pump discharge is known the required head is calculated from the pump curve. Then, the objective function is used to search for the minimum cost value. In that way, the cheapest pumping configuration that meets the established requirements is found (economic limitations, physical limitations, others). Nevertheless, in that context, it is not possible to find the maximum achievable cost saving since the optimal solution is restricted by the existing pumps characteristics. Therefore, more cost-efficient solutions can be found if the pump limitations are removed from the formulation either partially or totally. Following on from that, it is assumed that optimal pump configurations that fit the water network are not known. To obtain a greater degree of freedom with regard to the operation of the pumps, Fernández García, et al. (2014) and Fernández García et al. (2016) represented pumps as reservoirs in Epanet (Rossman 2000), considering the pump heads as decision variables. Their approach has been applied to irrigation networks. However, the interaction among individual reservoirs makes the behaviour and the optimization process much more complex. Thus, an alternative approach would be to assume that the pumps at the sources are supply nodes whose flow rates are decision variables, which is proposed in this work. In this way, the result is neither the flow nor the head a certain pump can provide, but the flow rate and pumping head required by the network.

The present work develops a new approach to achieving economic benefits through reducing energy costs in pumping stations. It aims to identify the least-cost flows for each of the pumped water sources in a supply network. To carry out the optimization process, two algorithms have been implemented and the results compared: 1) Hooke-Jeeves (1961), and 2) Nelder-Mead (1965). The algorithms are heuristic and do not guarantee that the global optimum can be found. However, the aim is to find a near optimal solution in a reasonable time. A strategy is employed to reduce the search space by discarding the infeasible solutions through the use of constraints. The methodology was developed using the EPANET toolkit (Rossman 2000) and Visual Basic via the Visual Studio 2010 platform. The objective function takes into account electric tariffs, water production costs, and pumping efficiency. Finally, two case study networks are analysed and the results and conclusions are presented.

PROBLEM STATEMENT

The approach uses the concept of a setpoint curve, where the most critical node in the network is identified and all of the pumping station are represented as nodes (Iglesias-Rey et al. 2012; Martínez-Solano et al. 2014; León-Celi et al. 2016). The critical node is used as a reference point to optimise pressure heads at pumping stations and satisfy the pressure requirements in the network, while keeping the energy consumption at the minimum. The critical node can change depending on the changing demand in the network, therefore, it has to be found for each time instant (step). By minimizing the pressure in the network, the leakage is also reduced and associated additional benefits are achieved.

The setpoint curve concept does not require the real pump as a hydraulic machine with its own pump characteristics (e.g., pump curve, efficiency curve, and power curve. It uses instead a node that represents a conceptual (hypothetical) pump, where for a given flow rate to be supplied at that node, the model determines the pressure head needed to supply the required flow rate. The values of both flow rate and pressure head for the conceptual pump are limited only by the required demand and the minimum pressure in the network.

As the setpoint curve deals with hypothetical pumps with not limitations on flow rate, it is not possible to associate an efficiency curve with them. However, as that is important to determine costs associated with flow rate and pressure head, the assumption taken here is that a constant efficiency value can be applied.

Obviously, the flow rate provided by the sources must meet demand requirements in the network. In the case of a network with several sources, the flow supplied by each source can take many different values. Every flow combination defines a specific setpoint curve for every source, which will also maintain the required minimum pressure. Hence, there are as many setpoint curves as source discharge combinations that will meet overall demand, but there is only one optimal setpoint curve. Thus, the cornerstone of this work is to find the optimal setpoint curve that leads to the minimum energy cost through the formulation of a cost objective function and the use of an optimization algorithm.

The basic assumptions of the methodology are as follows: (1) multiple water sources are available to supply water for consumption in the network; (2) each of the sources has its own pump(s); (3) storage is not available in the network and only snapshot hydraulic analysis is required to describe hydraulic behaviour of the system; (4) a setpoint curve for each pumping stations is obtained; and (5) the demand at nodes and demand patterns are known. This means that the flow rate and pressure head for each supply source is determined such that it satisfies both the demand in the network and the minimum pressure required.

METHODS

Objective Function

The least-cost solution is determined by optimizing the objective function that is formulated as the sum of the two cost terms. The first term represents the pump energy cost (Eq. 1) and the second is the cost of water treatment (Eq. 2). The analysis is developed for a 24 h time horizon with 1 h intervals. Therefore, 24 results are obtained at the end of the simulation period.

The first term in the objective function is obtained by multiplying the power consumption at the pumping station with the tariff unit charge and pumping time. In this case, the tariff function is represented as an average value per hour. Hence, it depends only on the energy consumed over the day.

$$EPC_i = \sum_{j=1}^{Nws} \frac{\gamma \times Q_{j,i} \times PH_{j,i}}{1000 \times \eta_j} \times ET_{j,i} \times t_i \qquad (1)$$

Where EPC_i is the sum of the power consumption cost for each pumping station *j* at hour *i* (€); Nws is the number of water supply sources, γ is the specific weight of water (9810 N/m^3); $Q_{j,i}$ is the flow rate for each pumping station *j* at hour *i* (m^3/s); $PH_{j,i}$ is the pressure head needed at each pumping station j at hour i (m); η_j is the minimum efficiency estimated for each pumping station j depending if it is desirable to incorporate partially the characteristics of pre-existent pumps or whether it is a new pumping system, j taken as a fixed value; $ET_{j,i}$ is the energy tariff at hour i (kWh/€) at the source j; t is the pumping time at hour i (h). The flow rate and the pressure head identify points on the setpoint curve for each pumping station. This concept will be explained with more detail in next section. It is important to note that as the proposed methodology involves simulation of the behaviour of unknown pumps, the efficiency value cannot be taken as flow rate dependent.

For the second term of the objective function, i.e., the cost of the treated water, is calculated as the product of the pumped flow rate and the cost of a cubic meter of treated water. Those costs are directly related to the volume of water produced.

$$TWC_i = \sum_{j=1}^{Nws} \left(TC_{j,i} \times Q_{j,i} \times t_i \right) \tag{2}$$

Where TWC_i is the sum of the treated water cost for each supply source j at hour i (€); $TC_{j,i}$ is the unit treatment cost for each water source j ($€/m^3$) at time i. $TC_{j,i}$ could also depend on aspects such as disinfection chemicals, maintenance, energy for the plant devices, and others.

The objective function can be expressed as follow:

$$\sum_{i=1}^{24} Min\, f(x)_i = \sum_{i=1}^{24} (\, EPC_i + \, TWC_i) \tag{3}$$

There are two types of constraints in the problem. The first are those related to the hydraulics of the system: 1) flow and energy conservation constraints; 2) pressure constraints, and 3) no negativity constraints for some variables. The second type of constraints are introduced to avoid infeasible solutions being evaluated:

a) The addition of each flow rate supplied to the network must be equal to the total flow rate(TFD_i) required at time *i*:

$$\sum_{j=1}^{Nws} Q_{j,i} = TFD_i \tag{4}$$

b) The total flow rate supplied by a water source cannot be greater than the total flow rate required and must be greater than zero:

$$0 \leq Q_j \leq TFD_i \tag{5}$$

c) The pressure head at the critical node (PHc_i) in the network cannot be lower than the minimum head required (PH_{min}):

$$PHc_i \geq PH_{min} \tag{6}$$

Setpoint Curve

A setpoint curve is a theoretical construct that allows setting both the specific flow rate and pressure head at the water source, which are needed to satisfy the minimal pressure constraint at the critical node. At the same time, it ensures that the water demand is met in full (León-Celi et al. 2016). Thus, the setpoint curve is represented by two variables, the flow rate against the pressure head. Furthermore, there is only one optimal setpoint curve for each water source. For a network with only one water source, the flow rate for every point on the setpoint curve will be the rate required at a particular time. With more than one supply sources, the problem of finding the flow rate and pressure head for each of them becomes more difficult since it is needed to determine both variables at the same time and there is normally interaction between the two sources. Hence, to define the curve it is essential to fix one of the two variables, either the flow rate or pressure head. The results obtained by employing the EPANET software are used for calculating the setpoint curve.

An easy way to determine the setpoint curve would be to fix one of the variables, e.g., the discharge from each water source. In other words, to determine a portion $x_{j,i}$ of the total demand to be pumped by station *j* at time *i* (Eq. 7). For that to be possible, the pumping sources need to be represented as nodes. By EPANET conventions, it also means that the flow rate will have to be negative at these locations. This allows a lot more freedom for selecting pump flows and heads than in the case with pre-existing pumps, because these values are not unnecessarily constrained. Since EPANET needs at least one water source where the pressure head is known, one of the sources must be represented as a fixed-head reservoir. This can be assumed for any of the sources. The reservoir will be necessary for adjusting the pressure at network nodes by varying its elevation.

$$Q_{j,i} = -x_{j,i} \times TFD_i \qquad (7)$$

Where $x_{j,i}$ is the part of the total demand to be supplied by the water source *j* in time period *i*.

The process begins with the fixed-head reservoir node (PH_{Rs}). Flow rates in other source nodes are allocated according to the second type constraints previously mentioned (Eq. 4 and Eq. 5) and the expression in Eq. (7). One additional constraint can be the maximum flow rate that a water source is capable of supplying. The flow rate of the reservoir and the pressure head of each water source will be calculated using this approach. Once variables have been initiated the hydraulic model is solved. Then the pressure in each node is evaluated and the critical node, having the minimum pressure (PHc_i), is found. Note that the critical node may change its position depending on demand variation over time. PHc_i is compared to the minimum required pressure (PH_{min}). If the required minimum pressure constraint is not satisfied, a correction to the reservoir elevation has to be implemented. For a single source, this is accomplished by increasing its value if higher pressure is needed or by decreasing it if it is lower, until the correct value is achieved. The number of corrective steps depends on whether the consumption in the network is considered pressure dependent or not. When the consumption is assumed not to be pressure dependent, only one correction step is necessary. Pressure dependent consumption makes the problem more complex due to two main reasons. Foremost, when the reservoir elevation is modified, it changes the pressure at every node including the critical node, and hence the demand flow rate. This often requires an iterative procedure. On the other hand, if the demand changes throughout the network, the flow supplied by each of the sources needs to be recalculated. For the cases studies the concept of emitters of EPANET was implemented for modelling pressure dependent consumption. However, modelling of water losses is considered beyond the scope of the present analysis and has not been implemented. The process finishes when the minimum pressure required is reached at the critical node (Figure 1).

The optimization problem arises when the pump flows from each source need to satisfy the minimal pressure head requirement and achieve the minimum costs are unknown. The procedure has to take into account that the distribution of pump flows affects the lowest cost that can be achieved. The problem can be addressed by testing a finite set of flow distributions among the sources to find which is the cheapest. However, a trial-and-error procedure can take a long time and still may not achieve the optimum. Therefore, the use of optimization algorithms is advisable, as explained in the next section.

The optimization function (Eq. 3) makes this a non-linear multidimensional problem with constraints. The number of dimensions is related directly to the number of water sources. The constraints (Eq. 4-6) have been incorporated into the problem indirectly by selecting a suitable flow distribution before the process begins and by correcting the elevation of the reservoir to keep the pressure within desirable values. The problem cannot be solved analytically, hence a search method is required. According to the requirements of the problem, two algorithms have been tested: Hooke & Jeeves (1961) and Nelder & Mead (1965). The main reasons for using these two algorithms is that they do not need complex mathematical operations and to compare their results. The algorithms have been implemented on the Visual Studio 2010 platform using the Visual Basic programming language that allows EPANET toolkit to be used. Both algorithms produced very similar results, thus only the results using the Hooke-Jeeves algorithm (León-Celi et al. 2016) will be presented.

CASE STUDIES

Two distribution networks have been considered in this paper, both with pressure dependent consumption. The first is the TF network (León-Celi et al. 2016), and the second is the COPLACA network.

TF network

This is a small network with eighteen nodes and twenty-four pipes. There are three water sources, P0, P16 and P17, in the system. In this case, the sources do not have flow constraints.

The source P16 is at an elevation of 4 m, and the elevation of the remaining sources is equal to zero. The average elevation of the network is around 5 m. Therefore, it can be considered as a flat distribution network. The emitter exponent used in this work is 0.5 and the emitter coefficient for each node is 0.8. The input data is shown in Table 1. The minimal required pressure is 45 m.

The electricity tariffs (Table 1) are different for each source and have been discretized into four periods. The prices correspond to the energy term in the expression for the energy consumed (Eq. 1). The maximum power has not been considered in this work. Both, the efficiency (η) and the cost of the water treatment (TC) is given for each source and they are assumed constant over time, P0 (η = 60%, TC = 0.30 €/m^3), P16 (η = 75%, TC = 0.25 €/m^3) and P17 (η = 65%, TC = 0.20 €/m^3).

Once the optimization is carried out, the setpoint curves for the three sources are obtained (Figure 3). Although source P16 is at a higher elevation than P0, the optimization results show that P0 is preferred over P16, i.e., the minimum energy curve is associated with P0. In other words, it is beneficial for source P0 to provide more water to the network than P16 in order to minimize the operation costs. Therefore, this demonstrates that the problem of finding the setpoint curves is a complex one, which cannot be understood by just observing pressure heads at various sources, but can only be solved by using an optimization approach. The optimized solution shows a flow distribution among the sources (Figure 4), which has not been obvious before optimization. For the first seven hours of operation, the source P17 makes the largest contribution to the system flows. This is logical as that is the source with the lowest electricity tariff for the period. As the demand increases, the contribution from source P0 increases in comparison to the other two sources. This happens despite it neither having the lowest tariff rate nor the best efficiency. Therefore, this shows that operating policies that lead to greater economic savings are difficult to infer. Although pumps selection is beyond the scope of this work, these curves can be very useful in selecting the pumping system.

It should also be mentioned that the minimum pressure in network over the whole simulation period is implicitly satisfied and guaranteed as part of the setpoint curve calculation process. Hence, addition another search objective or a constraint to meet this goal is not necessary. As consumption is pressure dependent it is important to keep the minimum pressure in the network, so use the septoint curve can mean significant savings, but the analysis of this aspect requires further research.

COPLACA network

The model was built for a real city with a population of 25,000 (Figure 5). It has a seasonally variable demand, which is particularly difficult to satisfy in the summer. The residential area does not receive enough water due to the increased water demand. Therefore, the municipality is considering additional water resources, which would involve reactivation of some old and neglected wells. The distribution network consists of 1,032 nodes, 1,095 pipes (a total length of 133 km), and one reservoir. There are seven water sources, six of them are nodes that represent pumping wells: P05, P06, P07, P11, P12, and P13. Each well has a maximum extraction flow rate (Q_{max}) associated with it. Reservoir P10 represents a river source, which supplies water through a pumping station. Consumption is considered pressure dependent. The minimum required pressure is 20 m.

In this case, a minimum (Q_{min}) flow rate for each water source has been fixed to avoid solutions with unrealistically low flow rates. The efficiency and the cost of water treatment of each source are presented in Table 2. They are assumed to be constant over time, as it was done in the previous case.

The demand curve was obtained for a period of 24 hours (Table 3). As in the previous case, the electricity tariffs have been specified for three separate periods, for each time step and the water source (Table 3). Prices are only a function of the electricity consumed.

In this case, it can be seen from Figure 6 that for most source the setpoint curves are flat and some of those collapse into a single point. The setpoint curve for P10 is the only one spread over the range of flows. This information can be used to support decisions on how to regulate the pumping systems for each water source, i.e., whether it needs variable speed regulators (e.g., P10) or can be kept as fixed-speed pumps. On the other hand, optimization (Figure 7) shows that all sources are required to work together only during the peak demand periods. Therefore, the results can lead to a better water management plan, including maintenance and operation plans, because only some of the water sources are required to meet demand at certain times of the day. As minimum pressures are also maintained, the consumption is kept low as it is pressure dependent. The river source (P10) has not reached its maximum capacity (Figure 6), thus allowing to eliminate need for additional sources. Hence, the existing network has enough capacity to meet the daily demand.

It is worth noting that if the source production costs are considerable higher than the energy costs and the differences among them are significant, the flows from different sources will be distributed mainly according to those rates, i.e. from the lowest to the highest cost. In that case, the energy cost may be less important. Therefore, optimization may arrive to an obvious answer. However, through the methodology presented it is still possible to find the least-cost flow distribution to be supplied by the different water sources.

CONCLUSIONS

This study considers pumping and treatment cost optimization required to determine the least-cost utilisation of multiple sources, from which the water is pumped into a water distribution system. For that purpose, the optimum flow rate must be found for each of the sources/pump stations over the period of analysis (e.g., 24 hours). The key to the methodology is the setpoint curve concept, which can be used with both pressure dependent and independent consumption.

In addition to the energy consumption, the objective function developed in this work allows consideration of additional aspects, such as water production costs, electricity tariffs, and the minimum and maximum flow rates for the sources. It is also possible to add any other consideration relevant for the particular network, e.g., water quality, as long as it can be expressed in terms of cost. To optimize the objective function, the use of an optimization algorithm is required. The algorithm must allow exploration of the wide range of water supply combinations among the water sources associated with pumping stations. In this case a direct search algorithms, Hooke-Jeeves, was chosen as it has been shown to be effective for nonlinear multidimensional problems with constraints. Although the method can encounter problems with local optima, it is efficient and quick to implement. Furthermore, the minimum pressure constraint is implicitly satisfied over the whole simulation period by the setpoint curve calculation process. As a consequence, there is no need to add another search criteria or an explicit constraint to account for that, as it is the case with other optimization approaches.

The problem of determining the optimum flow and pressure heads for each source/pumping station in a water distribution system is complex due to the non-linear nature of network behaviour, its topology, pressure dependent consumption, and variable tariffs. Therefore, it is difficult to infer optimal pumping operating policies without a formal optimization approach.

The case studies demonstrated the utility of setpoint curves as a method for determining a suitable least-cost pumping policy. By representing water sources as nodes allows this methodology much more freedom in selecting pumping policy that fits better network characteristics. It is also important to note that, if water production costs are more significant than energy costs, optimization will consider energy costs less important.

Further research will be directed to the assessment of benefits that supply source optimization can bring while considering leaks in the system. Moreover, the joint application of zoning strategies and management measures to improve the performance at the critical node have not been yet addressed. Furthermore, control valves, network storage capacity, pump selection, location of storage tanks, etc., have not been taken into account.

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Table 1. Demand curve and electric tariffs according to the hour and the water source (TF network).

Time (h)	**1-5**	**6-7**	**8**	**9**	**10**	**11**	**12**	**13-14**	**15**	**16**	**17**	**18**	**19-20**	**21-22**	**23**	**24**
Demand Factor (DF)	0.4	0.7	1	1.2	0.7	0.7	1.7	2	1.7	1	0.8	1.1	1.1	1.5	1.1	0.4
P0 (€/kWh)	0.094			0.133									0.166		0.133	
P16 (€/kWh)	0.092			0.131									0.164		0.131	
P17 (€/kWh)	0.090			0.129									0.162		0.129	

*Electric tariffs are variations of ENDESA (2017)

Table 2. Q$_{max}$, Q$_{min}$, performance and water treatment cost of the water sources of the network (COPLACA network).

Sources	**P05**	**P06**	**P07**	**P11**	**P12**	**P13**	**P10**
Efficiency (%)	60	75	65	70	80	60	70
Water treatment cost [€/m^3]	0.34	0.38	0.36	0.27	0.30	0.30	0.25
Q_{max} [l/s]	9.0	3.0	7.0	17.0	15.0	15.0	80.0
Q_{min} [l/s]	0.5	0.5	0.5	0.5	0.5	0.5	0.0

Table 3. Demand curve and electric tariffs according to the hour and the water source (COPLACA network).

Time (h)	**1-4**	**5-6**	**7-8**	**9**	**10**	**11**	**12-14**	**15**	**16**	**17-18**	**19**	**20**	**21-22**	**23-24**
Demand Factor (DF)	0.4	0.7	1.3	1.3	0.9	0.9	2.2	1.6	0.4	0.8	0.8	0.9	1.3	0.4
P05, P07,P13 (€/kWh)	0.090			0.129							0.162			0.129
P06,P11 (€/kWh)	0.092			0.131							0.164			0.131
P12, P10 (€/kWh)	0.094			0.132							0.165			0.132

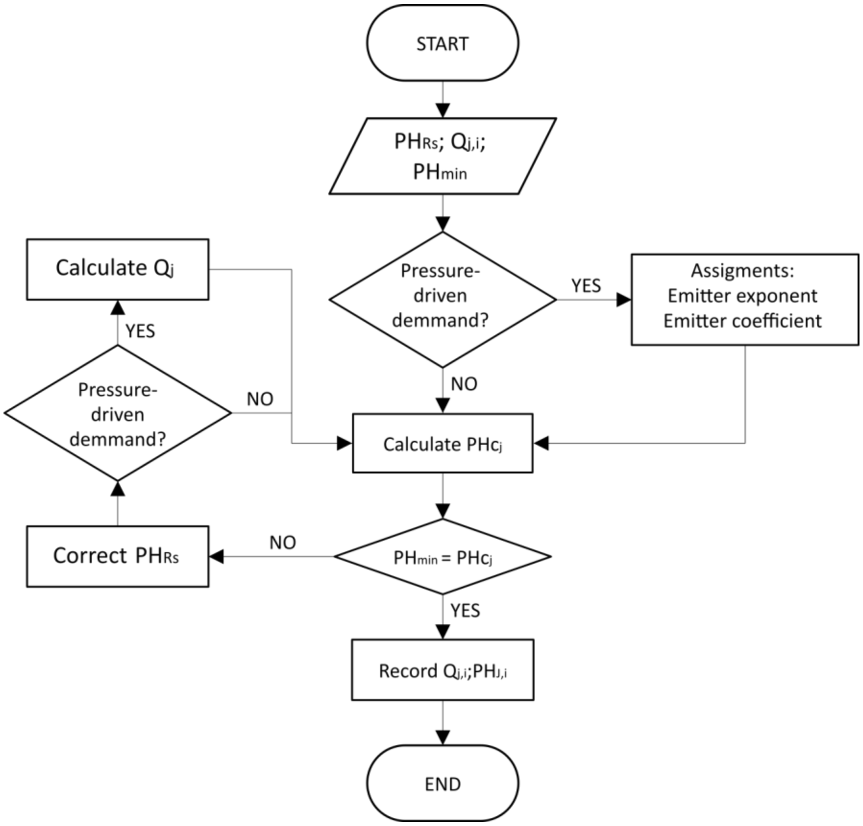

Figure 1. Setpoint curve. Calculation process.

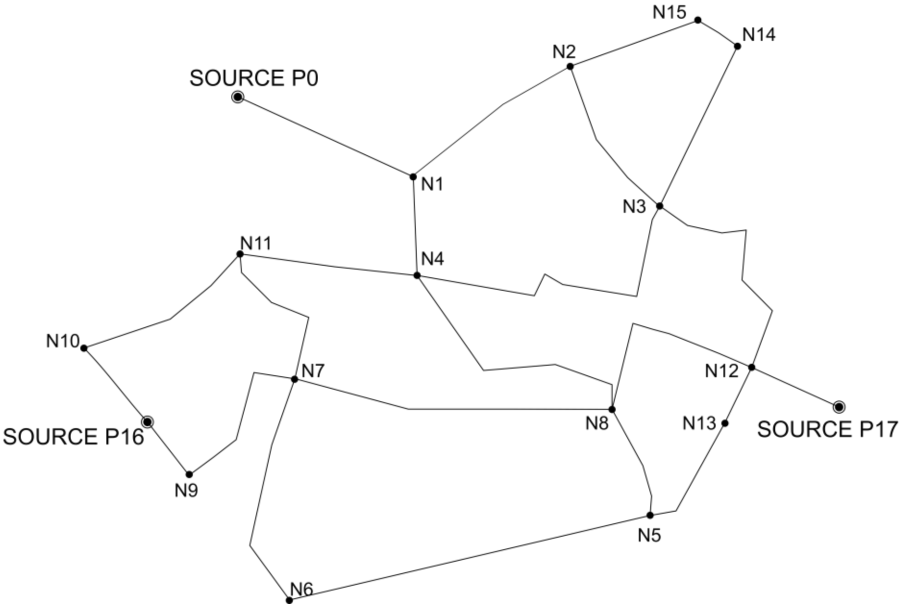

Figure 2. TF Network.

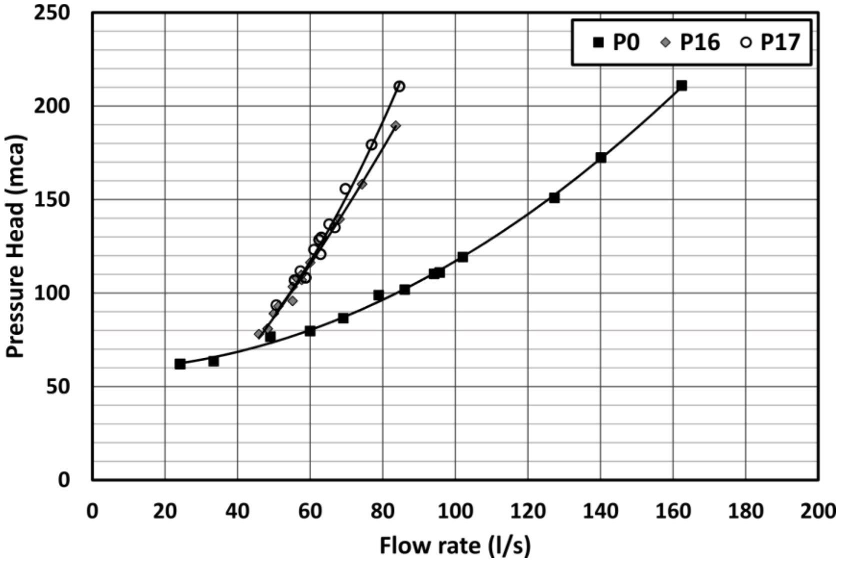

Figure 3. Setpoint curves from the TF network sources.

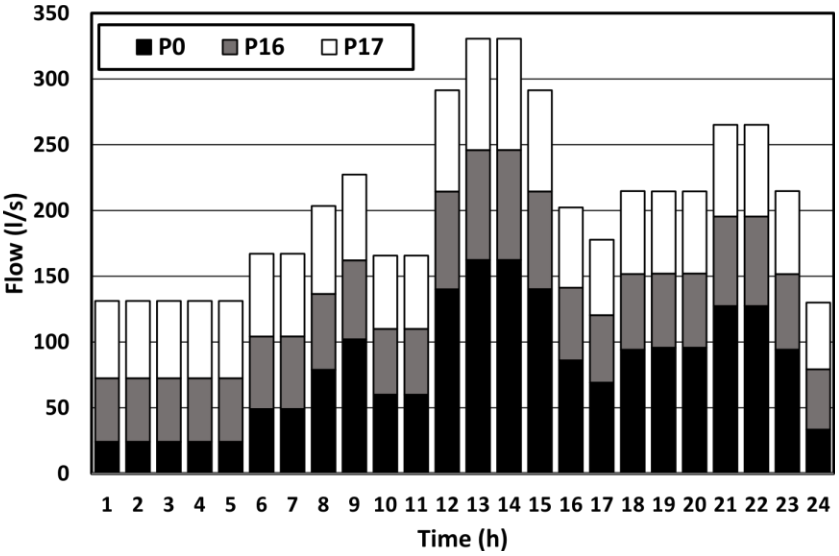

Figure 4. Flow contribution of each source in the TF network.

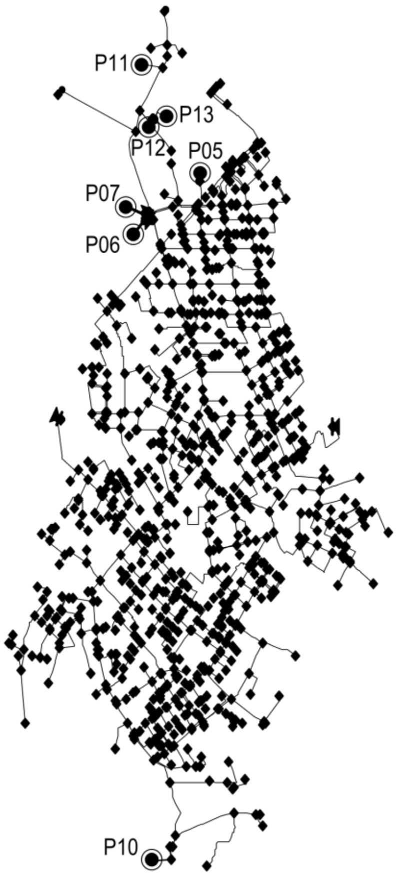

Figure 5. COPLACA network.

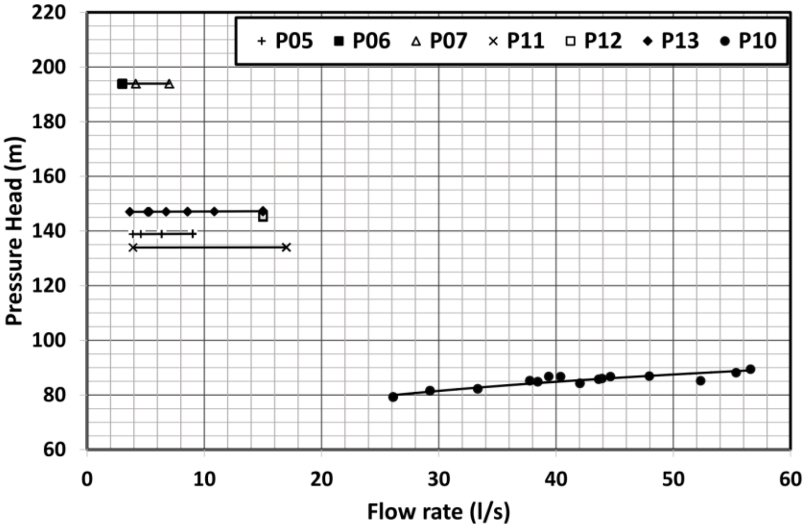

Figure 6. COPLACA network.

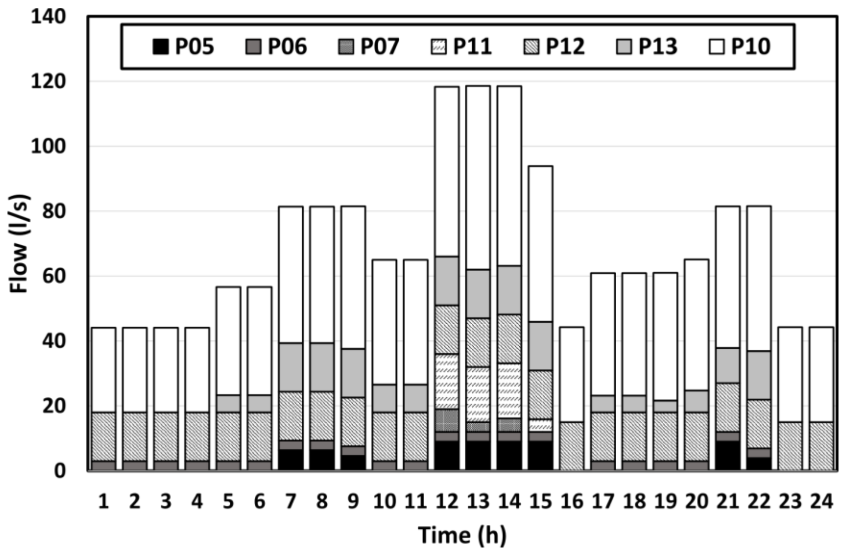

Figure 7. COPLACA network.