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Energy optimization of supplied flows from multiple pumping stations in water distributions networks

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Abstract

One of the most important concerns within the field of urban hydraulic engineers is the right management of water resources. When there is more than one water source, there is a question that must be answered: How much water should be provided by each water source according to the demand curve of the network? This work proposes a methodology that solves this question. It involves an energy analysis of the water network based on the concept of the setpoint curve. The setpoint curve gives, for every supplied flow, the minimum head needed to satisfy pressure requirements in the network. In this sense, the setpoint curve of every source relates two variables: supplied flow and minimum required head. Energy consumption in every source is evaluated by means of the product of these two variables. Then flow distribution among sources is optimized and minimum heads are obtained from the setpoint curve. The optimization process has been validated in two different ways. On one hand, a discrete method has been used, where a predefined combination of flow distributions are evaluated. On the other hand, the solution is found by means of Hooke-Jeeves and Nelder-Mead optimization algorithms. To apply these methods EPANET and its Toolkit has been applied to the mathematical model of the network. The optimization process can be applied to networks models with and without leakages. Finally, the methodology is applied to two cases, one academic network and real network where maximum flow limitations of every sources were also taken into account.

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Keywords: Energy; pumping; setpoint curve; optimization; pressure management

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1. Introduction

Pressure water distribution networks (urban, industrial, irrigation) always require new water sources supply as result of the demand increase, population growing, network extension, leakage rise, new service conditions and others. Water deliver requires energy to satisfy the network demands. In the case of distribution water networks are supplied by pumping, new sources represents an increase in energy consumption. In that context, any work related with water resource supply need to develop a feasibility study about the flow supplied by the source. At the same time an adjustment of nodal pressures to accomplish with the minimal pressure required can be developed. Moreover the nodal pressure adjustment can lead to an energetic optimization while network demands are accomplishing. To carry out the analysis it is necessary to answer the following questions: which are the optimal flow rates and head pressures to be supplied by each water source?, are the flow rates supplied effective to satisfy the network demand and keeping the minimum pressures?, how interact the different water sources and how important are they regard to the energetic consumption, what energetic implications represents a new water source?, how to get a lower energetic consumption?, and other similar questions.

Many works have been conducted to evaluate different strategies to get an optimal energetic consumption. For instance in arrangements of fixed speed pumps (FSP) one approach is the optimization of turns on and turns off of pumps by diminishing pumping cycles [1]. After this, variable speed pumps (VSP) were incorporated. These ones allow a better adjust between the pumping system curve and the resistant curve (system curve). That means that a reduction in the excess of energy consumption can be achieve to accomplish with the network minimal pressure requirements. VSP implementation can be complemented by fixing function restrictions to arise a pumping working at the maximum efficiency zones. [2]–[4]. When the system involves both FSP and VSP the energetic, optimization lies in a properly pumping selection as well as a suitable combination of them to aim a better adjustment with the system curve. Other works with multi-objective functions, search in addition cost optimization, therefore variables as network storage capacity and electric tariffs are included. In this way programming pumping groups to work at less energetic cost hours it is possible. This strategy is complemented with the control of the fill and empty levels of storage tanks [5]–[7]. On the other hand energetic consumption can be reduce with an appropriate pressure and leakage management. It can lead to a reduction on water demand as well as the need of energy. In irrigation systems a common strategy is grouping nodes that requires a high energy in hydrometric sectors. That allows to manage them efficiently [8]. Detection and manage of critical points on networks is also a measure adopted when exist the need of a reduction of the energetic consumption [9]. In irrigation systems the last two strategies can be combined with energetic tariffs and considers also more the one source of supply [10]. The aim is the cost reduction.

So far, many of the studies do not develop an explicit analyze of the interaction among the different water sources on a distribution network. Furthermore many of them only considers one water source supply. Besides and as was mention previously regulation of pumps is made taking as reference the system curve. Nevertheless in this work the use of the setpoint curve (SC) concept is proposed. The SC set point the pressure head and flow rate provided by each water source to accomplish with the minimal pressure required at the critical node or most representative node of the network [11], [12].

The present research propose a methodology where optimal flow rates and high pressures to keep the minimal pressure requirements can be founded by mean of the setpoint curve. Therefore optimal energetic consumption can be reached. This methodology can be addressed by two approaches. First one called the discrete method, refers to find the best solution after evaluate a set of possibilities previously defined. Second one or continuous method is based on the application of optimization algorithms. In this case Hooke and Jeeves [13] and Nelder Mead [14] were applied. The methodology has two levels: the first level corresponds to the optimization problem, and second level to the hydraulic model. Both are solved through EPANET software [15] and its TOOLKIT. Two study cases are studied. First one is an academic network "CT1" where consumptions are not pressure dependent. In the second one a real network is analyzed: the COPLACA network.

In the second section methodology to build the setpoint curve when exist more the one source of supply is explained. In section three the objective function as well as its restrictions are developed. Both discrete and continuous methods are described in section four. The study cases are presented in section five. Finally conclusions and future develops can be founded at the end of the document.

2. Setpoint Curve (SC)

The setpoint curve is built representing the head pressure which is necessary to deliver a specific flow rate keeping the lower pressure possible at the critical node of the network. The critical node is the most representative node in the network with the lowest pressure. It can change depending of the demand variation. However the SC will be the same. There are as many setpoint curves as sources of supply on the distribution network. The process to calculate the setpoint curve is related with two aspects, the number of sources (Ns) and whether the consumptions are or no pressure dependent.

A hydraulic model developed in EPANET with only one source of supply and no pressure dependent consumptions can be used as a simple case to calculate the setpoint curve. For each demand that corresponds to the flow supplied by the source in the moment (i) (Qs_i), an initial total head is assigned to the reservoir (H_0). The total number of scenarios (Nsc) to analyze corresponds to the total demand for each moment (i) and it must be defined previously. Then the critical node have to be identified as well as its pressure (p_{min}). Both the pressure of the critical node and the value of the minimal pressure required on the network (p_{req}) are contrasted. In this way the excess or deficit of pressure ($p_{e\text{-}d}$) can be calculated. The reservoir total head for the instant i ($Hres_i$) is the result of the correction of the initial total head taking as reference the excess or deficit of pressure. In this case the correction is made only once. At the last step the flow rate (Qs_i) and head pressure of the reservoir ($Hres_i$) for each scenario are represented. When hydrualica model involves pressure dependent consumptions the correction of the $Hres_i$ becomes in an iterative process. It means that every time that reservoir total head change the consumptions and all pressure will do it as well. The adjustment of the $Hres_i$ finish when the difference between the minimal pressure and required pressure is null.

When there are more than one water source supply, it must be took in account that only one node must be represented as reservoir. The reminded sources will be represented as injection nodes. In this case the first step is to fix the flow rate (Qsn_i) to be supplied by each source (n) in every moment (i). For each moment the flow rate supplied must meet with the total flow demand (QTD_i). In the reservoir case to fix the flow is not possible. This is calculated automatically by EPANET as the necessary flow to meet with the total demand. Later an initial reservoir total head is assigned. Then the procedure is the same as was explained in the case of one source. The setpoint curves are constructed with the flow rates (Qsn_i) and head pressures (Hn_i) of each source (n) for every moment (i). In this case it must not be forgotten that to calculate the head pressure of the reservoir is necessary to discount the value of the elevation. This methodology is valid while the consumptions are no pressure dependent. In the opposite case the flow rate to be supplied by each source (n) must be fixed as a fraction (xn_i) of the total demand. It lies on the fact that with every change in the total head of the reservoir demands change and flows supplied have to be recalculated.

$$Qsn_i = xn_i \times QTD_i \tag{1}$$

An overview of the process to define the setpoint curve in the different cases is shown in the next figure 1.

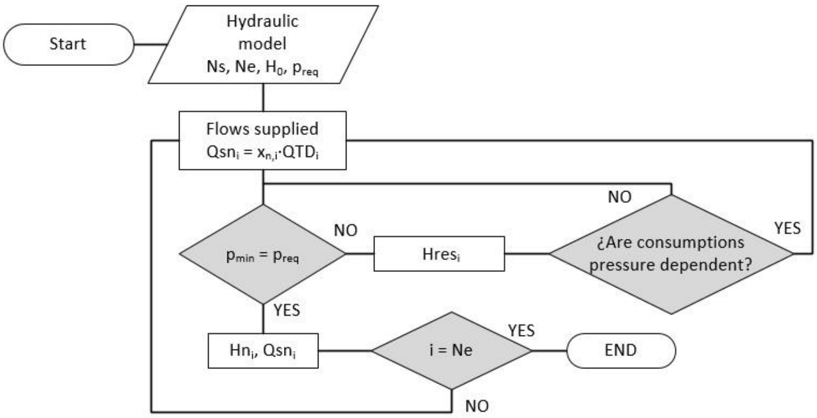

Fig. 1. Process to get setpoint curve (SC)

3. Objective function

As was said in the previous section, to obtain the head pressures of every source the flow rates to be supplied have to be fixed. However the problem emerge when the flows to be fixed are unknown or when the optimal flows have to be searched. It means the optimal combination (c) that leads to the minimum energetic consumption on the network. The total number of combinations (Nc) is related with the total number of sources (Ns) that are present on the same water network. The objective function to minimize for each moment (i) involves the sum of the product between the flow and head pressure of each source of supply (equation 2). Two elements are differentiated in the function. First one belong to the fixed flows of the supply nodes. The second one represents the reservoir. It must be taking in account that the total reservoir head is equal to the piezometric high, therefore the elevation (Helev) have to be took off. The total number of optimizations of the function for each time (i) depends on the total number of scenarios considered (Nsc). That is, the total demanded flow rates.

$$\min[f(x)_i] = \sum_{n=1}^{Ns-1} xn_{c,i} \times QTD_i \times Hn_{c,i} + \left(1 - \sum_{n=1}^{Ns-1} xn_{c,i}\right) \times QTD_i \times (Hres_{c,i} - Helev) \qquad (2)$$

Where, $xn_{c,i}$ is the flow assigned to the source (n), for the combination (c), in the moment (i); QTD_i is the total demand on the moment (i); $Hn_{c,i}$ is the head pressure of the source (n), for the combination (c), in the moment (i); $Hres_{c,i}$ is the total head of the reservoir for the combination (c) in the moment (i); and Helev is the elevation of the reservoir.

The address only the feasible solutions the objective function have to accomplish with the following restrictions:

- The sum of the fraction of the total flow demanded at the moment i assigned to each water source for the combination (c) must be equal to the unit.
- While exist more than one source of supply the fraction of the total flow demanded that one source can supply is within cero and one.
- Other restrictions obey to the hydraulic model and they refers to mass and energy conservation as well as non-negativity of some variables.
- One of the main constrains that is based on the setpoint concept is the one where the pressure of the critical node must be equal to the minimal pressure required on the system.

4. Methods to solve the objective function

As a function of how are flow rates of sources fixed the objective function can be addressed by two methods: the discrete method and the continuous method.

The discrete method implies to evaluate a finite number of combinations of flow rates to be supplied by each water source. The aim is to find the minimum value of the function. The total number of combinations depends of the incremental value added to the fraction of the total demand fixed for every source (Δxn). For little incremental values there will be more flows that need to be evaluated by source. Besides a major number of sources is equivalent to a major number of combinations to be addressed. In all cases the number of combinations must accomplish with the first restriction mentioned above.

The application of the continuous method refers to find the optimal combination of flows to be supplied with the minimal energy consumption without evaluate the wide range of possible combinations when are tested small values of Δxn. It can be achieved by means of optimization algorithms. In the present study and with the objective of validate the results two algorithms were applied: Hooke and Jeeves and Nelder Mead. The criteria to select the algorithms answer to a non-lineal multidimensional problem with restrictions. The algorithms applied are direct search methods due to the difficult to obtain the derivative of the function.

Hooke and Jeeves algorithm has two movements of search: one of exploration and other of jump. The exploration movement is in charge of analyze each dimension of the problem. To execute an exploration movement some parameters have to be defined. The parameters are: starting point, path length, and stop value. For lower values of the path length better solutions can be founded, nevertheless that represents a bigger computational time. Moreover through the stop value the result of each function evaluation can be compared with previous values. Whether the stop value is too small the time of calculation increase considerably. When exploration movement finds a better result for the objective function then a jump is done in that direction. In the opposite an exploration of the surrounds of the best result is made. This algorithms has problems with local optimal. Therefore is convenient to limit the search space by mean of restrictions in the section above. An additional measure to ensure the localization of the global optimum consist and execute the search from different starting points. In the present study values of 0.1 y 0.0001 for path length and stop value are assumed respectively.

The Nelder Mead algorithm requires initially a major number of function evaluations than Hooke and Jeeves. Each evaluation correspond to the n+1 vertexes of a simplex. Depending of each of the values of the initial function evaluation four movements can be made: reflection, expansion, contraction, and shrink. In each movement the simplex is rebuilt. The reflection movement objective is eliminate the worst value of the initial simplex. If after the reflection movement a better value appears the expansion movement is executed. On the other hand if the resultant value is between the two worst values the next step is the contraction movement. If after the reflection movement a better value does not appear the shrink movement is applied. The interactions of the algorithm finish when the criteria stop previously defined by user is accomplished. In this study the stop criteria obey to the difference between the values of evaluate the function for each vertex. It must not be superior to 0.0001.

5. Case studies

5.1. *CT1 network*

The CT1 network (figure 2) has 3 water sources: F1, F2 and F3. The consumptions are no pressure dependent. The average demand is equal to 154.20 l/s. The minimal pressure required is $p_{req}=45\ mca$. The hydraulic model is composed by 30 pipelines and 19 consumption nodes. The CT1 can be considered as a flat network since the average elevation is around 7 m and topography do not present considerable variations.

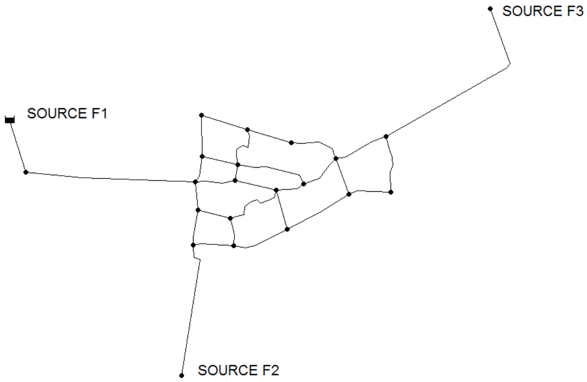

Fig. 2. Network CT1 with 3 water sources supply

To find the optimal flow rates to be supplied by each water source an $\Delta xn=0.1$ was considered in the case of the discrete method. In the case of the continuous method both algorithms mentioned above were applied. The range of flows analyzed is within 0.05 to 2 times the average diary demand with increases of 0.05 each time.

In figure 3 the results of both discrete and continuous methods are presented. Since the results of applying the two algorithms are very similar, only those obtained of the algorithm of Hooke and Jeeves are presented. At first sight the flows supplied don not change while de demand factor increase. Source F2 assumes the lowest fraction of the total demand. Since an energetic point of view the source F2 is the one which needs more quantity of energy. If both methods are compared, the continuous method presents more accuracy results. It this way continuous method can be the base for later works like the sizing of pumping stations starting of the flows and head pressure that minimize the energetic consumption.

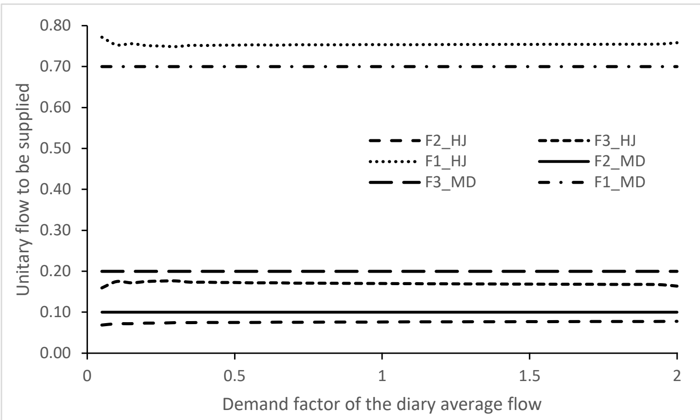

Fig. 3. Results of discrete *and continuous* method. CT1 network

Already results are very similar between algorithms, since now only results corresponding to Hooke and Jeeves will be shown.

5.2. COPLACA network

The network on figure 4 is located in the south of the Plantío and Cañada location. In this case the aim is evaluate ¿which are the optimal flow rates to be supplied by each water source? And ¿which sources must keep functioning?. The network has eight water sources: P05, P06, P07, P11, P12, P13 y D10. The source D10 represents a river that supply water by mean of a pumping station, and remaining sources correspond to pumping wells. The minimal pressure required is p_{req} = 20 mca. Consumptions are pressure dependent.

Fig.*4*. *COPLACA n*etwork

One important difference with the network above is the consideration of maximal flow capacity of each source. They are the following: P05 (9 l/s), P06 (3 l/s), P07 (7 l/s), P11 (17 l/s), P12 (15 l/s), P13 (15 l/s), y D10 (80 l/s.). The bigger difference of level among the network nodes is 53 m and the average elevation is around 100 m, therefore the relief of the network is appreciable. The network has 1032 nodes and 1095 pipelines.

In the figure 5 it can be noticed that the source with supplies more quantity of flow is the source D10. It means that D10 has the lowest energy consumption. As soon as one source reach its maximal capacity the next with the lower energetic requirements starts to work. Besides, some sources like in the case of P05 beginning to supply water before others that have a major physical capacity. In addition it can be seen that P06 and P07 water sources do not supply any water to the network. Hence an analysis of external factors that shows the relation between operational cost and keeping them working could be required. In this sense the relevance of each source of the network becomes evident. Beyond the final results can be useful to formulate an operational plan for pumping stations, as well as maintenance, maximal flow capacity, optimal location, and others. Otherwise an interesting approach can be the analysis of leakage management starting of the optimal flows and minimal head pressures requires by each water source.

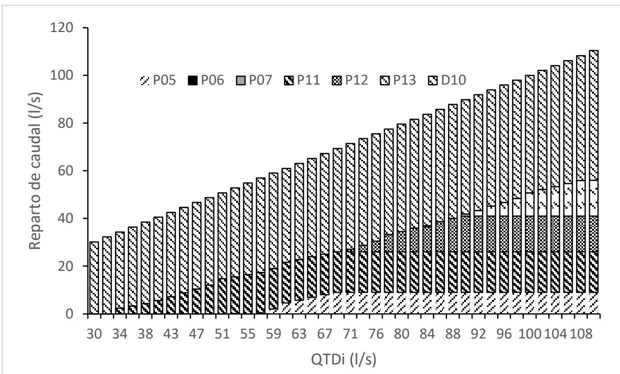

Fig.5. Optimal distribution of flows among water sources. COPLACA network

6. Conclusions and future developments

In accordance with the case studies, the useful of the septoint curve to find the optimal flows rates to be supplied by each water source and their head pressures keeping the minimal energy consumptions is evident. The optimal distribution can address problems like the analysis of new operational politics for the water sources, evaluation of the need of new sources, optimal location, the importance of every source in function of the flow supplied and energy consumption, and so on. Moreover to keep the minimal pressures on the network can be the base of leakage management control politics.

The discrete method requires of an appreciable quantity of time calculation due to the necessity of probe each possible solution. In this ways is impractical being even more problematic when the number of sources increase. The selection of algorithms responds to a non-lineal multidimensional problem with restrictions. Therefore they are enough efficiently and simply to address the formulated problem. The use of more complex algorithms depends of the number of variables to be considered in the objective function.

In this work the sizing of pumping stations has not been considered. Nevertheless, the setpoint of every water source can be used as base to solve it in future works. Other elements that have not been took in account are the network storage capacity, electric tariffs, regulation elements, which are aspects that need further research.

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