

# Pumping Cost Optimization in Looped Water Networks with Storage Capacity through the Searching of the Setpoint Curve

Christian-F. León-Celi<sup>1</sup>, Pedro Iglesias-Rey<sup>2</sup>, F. Javier Martínez-Solano<sup>3</sup>, D. A. Savić<sup>4</sup>, L. S. Vamvakieridou-Lyroudia<sup>5</sup>

<sup>1,2,3</sup> Department of hydraulic and environment. Politécnica de Valencia University, Valencia, 46022, Spain

<sup>4,5</sup> Centre for Water Systems. University of Exeter. North Park Road Exeter EX4 4QF UK

<sup>2</sup>Pedro Iglesias-Rey (piglesia@upv.es)

## ABSTRACT

*The pumping cost optimization still being a priority to minimize the operating costs in a water network due to the high cost of energy. In that context before to optimize the operation of installed pumps, it is required to find out the optimal operational points of each pump station independently of its associated features of flow rate and pumping head that are limited and limit the optimal solution. Thus, the aim of this work is to find the minimum energy curve (i.e. flow rate and pumping head) with the minimum cost that should be follow by each pump station to keep the minimum nodal pressure required by the network within a specific storage range in the tanks. This concept is known as setpoint curve. The objective function to be minimized considers the pumping cost with a diary structure of the energy fare, the water treatment costs and penalty costs related to the nodal pressure and the storage capacity of the network. To carry out the optimization the Differential Evolution algorithm has been applied. The proposed methodology has been tested in the water network D-town BWN II which has five pumping stations and seven tanks. Results show the maximum savings that it is possible to achieve in pump stations and gives important information to select a suitable pumping system that fit with the optimal operation of the network.*

**Keywords:** water, optimization, pump.

## 1 INTRODUCTION

One of the priorities in decreasing operating costs in distribution networks is the minimization of costs of energy used to pump water. This can be done by a) diminishing either the discharge or the pumping head of the pump, b) enhancing the pumps efficiency, c) storing water in tanks at hours with low energy-fares, d) selecting the best pumping combination among the pumps installed, and d) by increasing the life of the pumps by means of the control of the starts and shutdowns of the pumps. Although some of these approaches usually are managed together most of the research works developed so far start with selecting the least-cost pumping combination. However, to achieve greater savings first it is needed to find the optimal discharge and minimum pumping head that each pumping station has to supply over the simulation period to meet the network requirements, which is the main aim of this work.

In general terms, the lowest operating costs are associated with the least-cost pumping scheduling. This can be calculated either directly or indirectly. The direct approach tries to find when and how much time each pump must be working over the simulation period. On the other hand, the pumping schedule can be found as a function of other variables: least-cost pumping discharge (or pumping head) of each pump, and least-cost trajectory of tanks levels. Therefore, the decision variables can be the time, the flow rate, the pressure head or the levels of the tanks. To find these variables

different programming methods have been implemented. Some early methodologies are linear programming, dynamic programming, and nonlinear programming [1]. However, most of them are subjected to big simplifications of the network and the number of tanks and pumps that are capable of managing. This is mainly because of the computational capacity of that time. As these drawbacks have been overcome new and complex algorithms have been applied such as genetic algorithms, ant colony, harmony search and others. Some of the approaches are focused in the speed of the search; hence, hybrid algorithms where more than one algorithm is used to improve the search efficiency have been formulated. Furthermore, other methods search beside the least-cost pumping scheduling other hydraulic benefits, thus multi-objective criteria have been included. Although, nowadays is possible to manage a big number of variables in regard to the pumps number (flow rate and pumping head) it would be more convenient to generate pumping policies for each pump station instead for each pump. Thus, the pumping scheduling can be addressed easily for each pump station separately. On the other side adding multi-objective search criteria, the problem becomes in more complex and sometimes these additional objectives are implicit and are unnecessary. Moreover, one common aspect of many methodologies is that they depend on the characteristic curves of pumps installed. Therefore, when the minimum cost that results of any cost optimization method is reached, the possibility to achieve major savings with a different pumping system is neglected. This means that some pump stations can be either oversized or undersized. In that sense, this paper presents a new approach that deals with three aspects: a) reduction of variables of decision (p.e. number of pumps), b) implicit multiobjective search criteria (p.e. minimization of operating costs and nodal pressure) and c) use of pumps with non-predefined curves.

The objective function to be minimized takes into account the sum of four terms. The first two are the cost of pumping based on a daily energy tariff structure and the cost of the water treatment. The remaining ones are penalty costs related with nodal pressure and storage volume constraints. It is important to emphasize that the cost of pumping is calculated over the concept of setpoint curve. The setpoint curve or curve of minimum energy is a theoretic curve that for a given pump discharge allows defining the minimum pumping head required to meet the demands, minimum nodal pressure, and storage levels in the reservoirs. For that purpose, pump stations are represented as nodes, that mean that they are limited neither flow rate or pressure head. Thus, the inputs of the optimization method are the discharges of every pump station and the outputs are the pumping heads.

The optimization of the objective function has been carried out by mean of the *Differential Evolution algorithm* [2] which is enough efficient to manage a non-linear, non-differential problem with restrictions and a big number of variables. The programming of the method has been done by mean of platform Visual Studio 2012 and the toolkit of Epanet.

Finally, the methodology has been tested taking as reference the optimized solution of the Battle of the Water Networks II from [3]. Results and conclusions are shown at the end of the paper.

## 2 METHODS

### 2.1 Setpoint Curve

The setpoint curve can be understood as the minimum energy required by each pumping station to meet the water demands of the network over the simulation period. Besides, at the same time the minimum pressure is kept at the critical node (i.e. node with the lowest pressure) [4], [5]. The

minimum pressure is an external constraint and depends on the design normatives. In order to calculate the setpoint curve it is assumed that a) the pump stations behave such as nodes that supply water to the network b) each fount of water has one pump stations associated though it is not accomplished in the case of booster pumps c) the hydraulic model is representative enough of the network. One the way to compute the setpoint curve is by Epanet software and the procedure will be described next.

The process will be different depending on the number of pump stations and if the network has tanks. When there is only one pump station and there are no tanks the pump station is represented as a reservoir, which means with unlimited water capacity. In this case, the network analysis will be static since there is not storage capacity. For that reason, the setpoint curve will be built over each demand change. In the first step, an initial value of the total head of the reservoir is allocated. Then, the hydraulic model is solved and the critical node is found as well as its pressure head. The next step consist in comparing between the critical node pressure and the minimal pressure required. Then, two possibilities are presented. The first one is that the pressure at the critical node be higher than the minimum pressure required, in that case, the value of the total head has to be reduced. On the opposite, if the value is lower the total head has to be increased. The convergence is reached when both the critical node pressure and the minimum pressure allowed are equal. Finally, the flow rate provided by the reservoir is got. The setpoint curve will have as many points as demand changes have been analysed.

In networks with more than one pump station but still not storage capacity the process is a little different. Only one pump station (it can be anyone) will be represented as a reservoir and the others will be represented as nodes. As in the previous case, a value of the total head of the reservoir must be given at the beginning. However, additional information should be provided. This corresponds to the flow rate supplied by each node (i.e. pumping station) into the network that meets the total consumption of the network over the simulation period. In terms of Epanet one node that supplies flow has a demand with a negative sign. Once the hydraulic model has been solved, the pressure head at the critical node should be corrected by changing the total head of the reservoir according to convenience. In this way, the outputs of the optimization process are the flow rate supplied by the reservoir and the pressure heads of the pump stations represented as nodes.

The last case includes the reservoir tanks, therefore the analysis will be done in extended period. In this case, all pump stations are represented as nodes with negative demand; hence, the pressure head at the critical node cannot be adjusted by changing the total head of the reservoir. This is because to fill the tanks sometimes it is required more pressure head than the minimum necessary at critical node, and other times the pressure will depend entirely of the tanks instead of the pumps. Therefore, the objective is no longer to maintain the minimum pressure at the critical node, but to maintain the minimum possible pressure either equal to or greater than the minimum required pressure. On the other hand, the discharge of the pump stations has to be enough to meet not only the consumption of the network but also to fill the reservoirs. The quantity of water to be supplied by each pump station can be stated as follows:

$$Q_{j,i} = x_{j,i} \cdot K \cdot Qmd \quad (1)$$

Where  $Q_{j,i}$  is the flow rate of the pump station  $j$  at simulation period  $i$ ;  $x_{j,i}$  is the variable of decision that defines the quantity of flow rate to be supplied by the pump station  $j$  at period  $i$ , it can take any

value between zero and one (0,1);  $K$  is a constant value that points out the peak flow over the whole simulation period; and  $Qmd$  is the average daily flow rate demand of the network.

The values of  $x_{j,i}$  must keep the minimum pressure possible at the critical node for each period of simulation and meet both the water demand of the nodes and tanks water requirements. As this values are not known an optimization process has to be developed. However, if the water flow and pressure head of the pumps are only analysed, the optimization will be done only from the energetic point of view. Hence, the influence of the energy fares as well as other costs have to be included as it is explained in the next section.

## 2.2 Objective function

The total costs (TC) of the objective function are based on the sum of two general terms. The first ones are the total operating costs (TOP) and the second ones are the total penalty costs (TPC).

$$\text{Min } (TC) = (TOP + TPC) \quad (2)$$

The TOP are the sum of both the pumping costs and the costs associated with the production of water. The final sum is done for both the number of pump stations ( $Nps$ ) and the total amount of periods of simulation ( $Tap$ ).

$$TOP = \sum_{i=1}^{Tap} \sum_{j=1}^{Nps} \left( \frac{\gamma \cdot Q_{j,i} \cdot H_{j,i}}{\eta_j} \cdot t_i \cdot EF_{j,i} + Q_{j,i} \cdot PF_j \cdot t_i \right) \quad (3)$$

Where  $\gamma$  is the specific weight of the water;  $H_{j,i}$  is the pressure head of the pump station  $j$  at period  $i$ ;  $\eta_j$  is the efficiency of the pump station  $j$ ;  $t_i$  is the pumping time over de simulation period  $i$ ;  $EF_{j,i}$  is the energy fare of the pump station  $j$  at period  $i$ ; and  $PF_j$  is the water production fare allocated to the pumping station  $j$ . This last term is only considered when the pump station is associated directly to a water source and there is more the one source.

The PTC are costs derived from the non-compliance of both the pressure constraints and the volume constraints of water stored in the tanks.

$$PTC = \omega_1 \cdot \sigma_1 \cdot \sum_{i=1}^{Tap} (Hr - H_{c,i}) + \omega_2 \cdot \sigma_2 \cdot \sum_{d=1}^{Ndt} (l_{1,d} - l_{Tap,d}) \quad (4)$$

Where  $\omega_1$  is a discrete variable that only can take two values zero or one. When  $H_r$  (minimum pressure required) is higher or equal to  $H_{c,i}$  (pressure on the critical node at period  $i$ ) its value will be zero, otherwise, it will be one and a penalty cost in the objective function will be added. On the other hand,  $\sigma_1$  is a conversion factor that transform the difference between pressures into cost. The  $\omega_2$  has the same function as  $\omega_1$  but its value will be zero when the level of the tank  $d$  ( $l_{Tap,d}$ ) at the end of the simulation period is higher or equal to its initial level ( $l_{1,d}$ ), but if the condition is not met its value will be one. The  $\sigma_2$  is also a conversion factor that transform the difference between levels into cost and  $Ndt$  is the number of tanks in the network.

It can be noticed that the aim of objective function is not only to minimize the pumping cost but also to keep the minimum nodal pressure on the network and keep the tank levels within a range established. Thus, there is not need to use multiobjective criteria since any additional task could be included in only one objective function as long as it can be expressed as a cost.

## 2.3 Optimization algorithm

In order to minimize the objective function *Differential Evolution* algorithm [2] has been applied. This is a parallel direct search method designed to address non-linear and non-differentiable functions; hence, it fulfils the requirements of the problem.

The first step of this method is to generate randomly NP parameter vectors of Nd dimensions. Nd is given by the product between the number of pump stations (Nps) and the total amount of periods of simulation (*Tap*). For this work, the value of NP has been taken as the same as Nd. Each one of the NP vectors has to be assessed. Then, a new population is generated by mean of three steps *the mutation, the crossover and the selection*.

The *mutation* can be done through different methods, but in this study the Eq. 5 has been used. This process has to be repeated NP times.

$$v_{i,G+1} = x_{r1,G} + F \cdot (x_{r2,G} - x_{r3,G}) \quad (5)$$

Where  $v_{i,G+1}$  is the vector  $i$  of Nd dimensions of the generation  $G+1$ ;  $x_{r1,G}$ ,  $x_{r2,G}$  and  $x_{r3,G}$  are random and no equal vectors of the generation  $G$ ; and  $F$  is a factor which controls the differential variation, the value applied was 0.5.

The *crossover* process is done between the elements of each one of the vectors of the generation  $G+1$  and the generation  $G$ . For that purpose the rules of Eq. 6 must be followed.

$$u_{ji,G+1} = \begin{cases} v_{ji,G+1} & \text{if } rand(j) \leq CR \text{ or } j = rand(i) \\ x_{ji,G} & \text{if } rand(j) > CR \text{ and } j \neq rand(i) \end{cases} \quad (6)$$

Where  $u_{i,G+1}$  is the element  $j$  of the vector  $i$  of the generation  $G+1$  after *crossover* step;  $v_{ji,G+1}$  is the element  $j$  of the mutated vector  $i$  of the generation  $G+1$ ;  $x_{ji,G}$  is the element  $j$  of the vector  $i$  of the generation  $G$  over the mutation is done;  $rand(j)$  is a random number  $\epsilon (0,1)$ ;  $rand(i)$  is a random number  $\epsilon (0,Nd)$ ; and  $CR$  is the crossover factor which value is 0.8.

Finally if the trial vector  $u_{i,G+1}$  produce a better value of the function than  $x_{i,G}$ , it will be member of the new generation as  $x_{i,G+1}$  but if the value is worst, so  $x_{i,G+1}$  will be equal to  $x_{i,G}$ . This process is known as *selection*. With the new population, the analysis is repeated once again until reaching the stop criterion that must be previously established.

## 3 Case Study

### 3.1 D-Town Water Distribution Network BWN-II

The method has been tested by mean of the D-Town Network [6] that is presented in Figure 1. Despite the aim of the original problem is to find design improvements regard pipes, tanks, valves, pumps and others, this work is only focused on the optimization of the pumping system. For that reason, it has been taken as reference one solution previously optimized [3]. The complete description of the network can be found in Exeter, 2017 [7]. The network has thirteen pumps divided into five pump stations that are named with the prefix ‘‘S’’. The pump station allocated to the water source is the pump station S1, therefore, the remaining ones are booster stations. Besides, there are seven tanks. It is worth to highlight that Figure 1 shows the model of the network used to apply the method proposed, therefore, the pump stations are represented as nodes. In places where there are booster pumps (nodes with negative demand), it is needed to create nodes with the same

value of demand as pumps but with positive sign. This will help to keep the continuity of the demand on the water network.

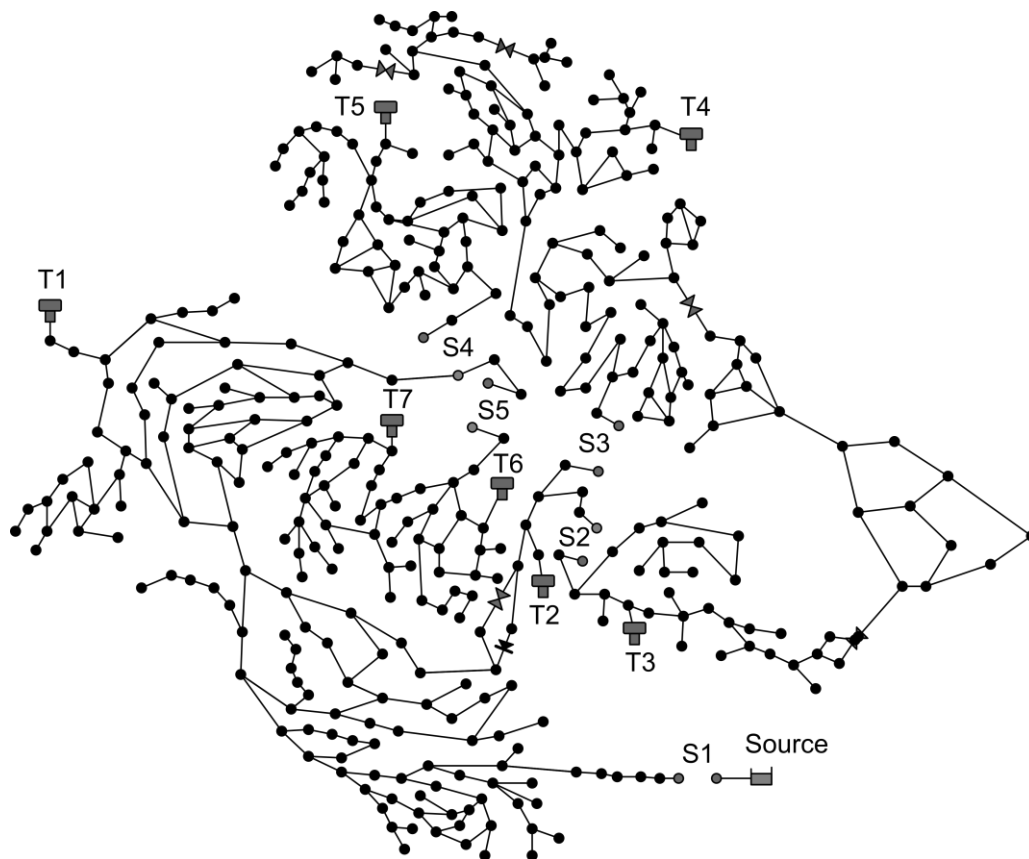


Figure 1. D-Town water distribution network. Setpoint curve model

The starting solution [3] has two pumps with an efficiency of the 75%. Therefore, with the aim of making an analysis in equal conditions, the efficiency of all pumps has been fixed in 65%. The analysis has been performed for a 24 h period. The pumping cost of the reference solution is 380895.75 \$/year. Once the proposed method has been applied, the minimum cost reached was 300952.00 \$/year; hence, the saving achieved was around 21 %. Although the value of savings is quite big, this only can be reached by mean of a different pumping system than the currently installed. In Figure 2 it can be seen the characteristic pump curves of each pumping station vs the points of the setpoint curve. With the got information it is possible to select a pumping system more suitable to the minimum pressure requirements of the network. Therefore, it will be easier to select properly the pumps number and its type (i.e. fixed speed pumps or variable speed pumps). Moreover, strategies to regulate the flow rate and pumping head of each pump increasing the efficiency and reaching higher savings can be created. In Figure 3 tank levels at the end of the simulation period are the same or higher than the beginning. However, the tanks T2 and T6 are full of water almost the whole day. In the first case, the level of the tank T2 depends on the control of the valve V2, which keeps the tank full. In the second case tank T6 receives water from tank T7 with a higher elevation, thus it keeps its level at maximum. Therefore, both tanks seem as they have not been optimized though that is not true.

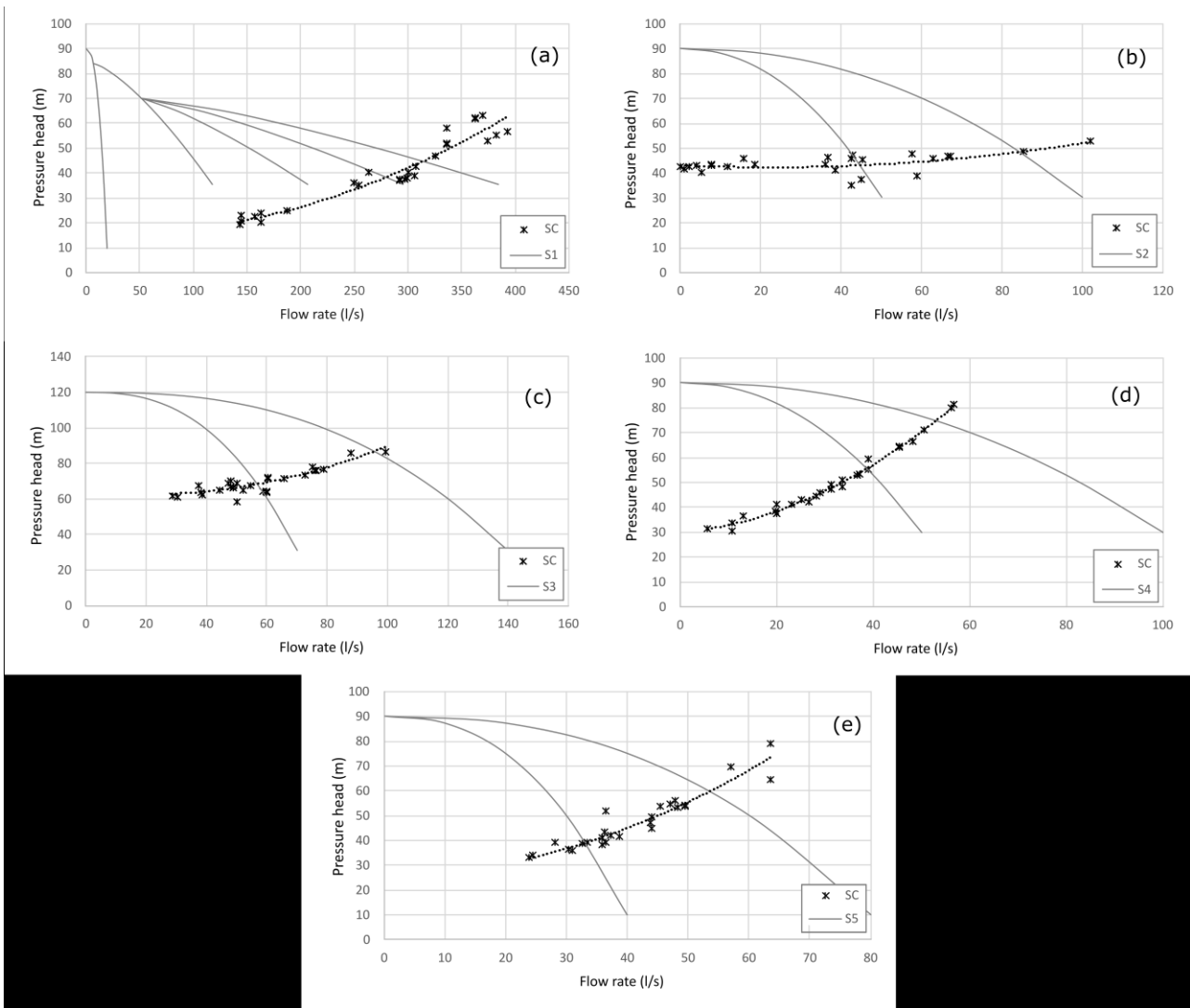


Figure 2. Pump curves vs points of the setpoint curve. Pump stations: (a) S1, (b) S2, (c) S3, (d) S4, and (e) S5

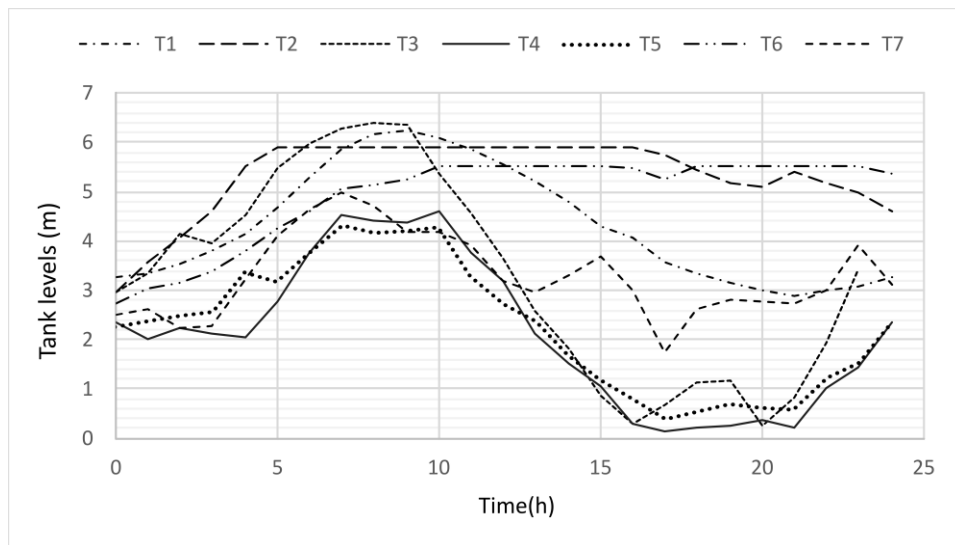


Figure 3. Levels of the tanks over the simulation period

## 4 CONCLUSIONS

A new approach to minimize pumping costs has been presented based on the setpoint curve concept. The method relies on finding the optimal operations points (i.e. flow rate and pumping head) of each pumping station keeping the minimum pressure possible at the critical node on the network over the simulation period. For the optimisation model, pumps are represented as injection nodes. The model inputs are the discharges of the pump stations and the outputs are the pumping heads. In this way, pump stations are not limited in either flow rate or pumping head. For calculating the costs, it has been considered two general costs, the operating costs and penalty costs. The operating costs involve the pumping costs with a daily structure of the energy tariff and the water production costs. The penalty costs depend on the constraints of both pressure and tanks storage.

To minimize the objective function, *Differential Evolution* algorithm has been applied. This algorithm responds to a non-linear, non-differential, multidimensional problem. It worth to highlight that the aim of the work is not to test different optimization algorithms but the utility of the proposed methodology. However, the applied algorithm has proved to be robust enough to deal with a big number of variables and problems of local optimal. Besides, it is easy of programming.

The D-Town water distribution network has been used as a demonstrative problem. Results show that it is possible to reach major savings (i.e. until 21%) with a different pumping system instead of the currently installed. The got information (i.e. setpoint curve points) makes more visual the pump stations that works under either an excess or deficit of energy. Therefore, it is possible to know if pump stations are oversized or undersized.

This method will be useful to select a more suitable pumping system under pre-established conditions of pressure and storage capacity of the network. Besides, it could help to create a high-efficiency pumping scheduling. On the other hand, aspects as a more complex structure of the energy fares as well as the sizing of the tanks could be included in the analysis. However, further research is required.

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