BATTLE OF INTERMITTENT WATER SUPPLY INSTRUCTIONS
(21/11/09)

1   BACKGROUND

Intermittent water supply affects 1.3 billion people worldwide, mainly in South Asia, Latin America and Africa. The main cause for this situation is due to lack of maintenance and lack of control of consumption, which greatly increases leaks. A network with uncontrolled demands cannot be pressurized beyond a few meters of water column. A common solution to recover some pressure in the network is to fall back on intermittent supply by zones. There is great interest worldwide in recovering the 24-hour continuous supply in these networks and restoring the supply pressures to acceptable values.

When a water distribution network (WDN) is designed, the aim is to satisfy all demands while guaranteeing enough service pressure at all nodes. The reservoirs play an important role in this, and they are designed with a sufficient level and capacity. In many cases, pumping is necessary to fill the reservoirs or to provide sufficient pressure if pumping supplies the network directly.

However, many WDNs in developing countries do not currently meet the service guarantees that were originally planned. This may be due to a shortage of resources, such as the depletion of certain boreholes or a decrease in surface flows, but above all this is due to a lack of maintenance of the network and the lack of demands control.

When the increase in leakage or demand exceeds the transport capacity of the network, or the latter is reduced due to the deterioration of the pipes, supply pressures are reduced, especially during peak demand hours. A first solution is to build elevated household tanks on the roofs of houses to supplement the lack of supply during peak hours, and to wait for the tanks to be refilled during off-peak hours and at higher pressures.

At a later stage, as leakage and uncontrolled demand increases, the night-time pressures may not be sufficient to refill the above-ground tanks, and the next solution is to install an above-ground tank at ground level or in the basement with a larger capacity. From this, the above-ground tank can be refilled periodically by pumping, or a direct supply can be made by means of local pressure equipment.

However, the pressure in the network may not be sufficient to fill all the surface tanks available in the network. The next step is to sectorise the network to provide intermittent supply, where users have water only for a few hours a day. By reducing the total demand at a given time, pressures are partly recovered by reducing losses in the conveyance system from the supply source to the sectors in operation.

An alternative solution would be to control demands by installing flow restrictors at the consumption points, but in practice this solution is only feasible for a few consumers. Therefore, taking into account the limited resources feeding the reservoirs, a common practice is to limit the flow supplied from the reservoirs by installing a throttling valve at the outlet, which prevents any excessive consumption (leaks or demands). In many cases this leads to negative pressures downstream of the valve, which in turn causes air to enter the pipelines.

To partially alleviate the problem of limited flow from the main reservoirs, alternative sources of supply are often sought, especially well pumps. At the outlet of these well pumps, limiting valves are also installed to control the flow rate extracted, which can in turn cause downstream depressions and the entry of air into the network. The shift change from one sector to another also facilitates the entry of air into the pipes of those sectors that are out of service at any time. Finally, the presence of air in the pipes causes new breaks and leaks, which ultimately further increase the problem.

2   OBJECTIVES OF THE CHALLENGE

The challenge proposed in this Battle of the Water Networks focuses on establishing the best strategy for the rehabilitation of a deteriorated network, with intermittent consumption by sectors and with users who have household reservoirs. This rehabilitation will be carried out with a fixed amount to be invested over 5 years. The objective is to meet the criteria for which the network was initially designed: continuous supply to all users, minimum pressure at all nodes. The different possible actions to be carried out are repairing leaks, replacing

pipes, installing new pumps or expanding the tanks capacity. The results of these actions can be measured through a series of indicators that measure the hours of availability of the resource per user, the number of users with continuous supply, the supply deficit, the volume leaked, the supply pressure, the energy consumption or an estimate of the amount of air present in the pipes. The desirable solution would be a direct supply with reasonable service pressures, similar to those envisaged when the network was initially designed.

3 INITIAL ASSUMPTIONS

In order to make the development of such a broad challenge manageable, and to standardize the proposals of the different participants, a number of simplifications and initial assumptions to be taken into account are introduced below:

3.1 About resources

Each supply source has a maximum capacity that is allowed to remain constant throughout the simulation period. The possible sources of water supply in this problem are listed in Table 1. This table lists the six available supply sources, the type of source (natural spring or well), the head of water at the source and the maximum flow that can be supplied. In the case of the head of water, the interpretation is different depending on whether the source is a spring or a well. In the case of the only existing spring, the water level is the level of the reservoir that collects the water and supplies it to the network. In the case of a well, the water level represents the elevation at which the well's diurnal level is when the pumps are running.

Table 1. Data from E-Town supply sources.

Source Id	Source Type	Head of water (m)	Maximum Flow Rate (MFR) (l/s)
R1 (Main Tank)	Natural Spring	164.95	200
W1_RI	Well	13.0	20
W2_SA	Well	58	10
W3_AB	Well	52	15
W4_SM	Well	32	40
W5_PL	Well	25	15

The Main Reservoir is fed from a spring whose maximum flow rate (MFR) is fixed throughout the year. To represent this limitation, a flow limiting valve has been installed at the outlet with a fixed value equal to the MFR of the source. This valve will open fully when the flow rate through the pipe is less than the MFR. When the flow rate demanded is higher than the MFR, the valve will introduce a head loss generating negative pressures in the pipe in order to control this flow. This will represent that the pipe downstream would not be operating as a pressurized flow but as a free surface flow. The MFR that can be supplied from the Main Reservoir is given in Table 1.

3.2 On infrastructure

The causes of intermittent supply lie solely in the deterioration of the infrastructure (leaks and reduced capacity) and uncontrolled consumptions. The network layout remains unchanged for the entire 5-year period. However, the regulating elements of the network may be modified. In addition, as many control elements as necessary can be added. Each of these has an associated cost, as defined below.

Restrictions on adding new elements to the network are as follows:

- Valves may only be installed in existing pipes. In such cases, the diameter of the valve must be as close as possible to that of the pipe in which it is installed. The valve can be added at either end of the pipe. To do this, a new node must be created at the same level as the node at which the valve is connected. Only pipes may be reused. It will not be possible to lay new pipes not initially defined.

- Pumps may only be installed at those points where they have been previously defined. Pumps currently installed may be used. Existing pumps can be replaced by new ones, taking into account their investment costs. None of the existing pumps have a frequency inverter. However, it will be possible to incorporate such a frequency inverter in any of the pumping stations. In this case the cost of installation of these devices will also have to be considered.

3.3 On the initial situation of the network

All network hydraulic model data are collected in the BIWS.inp file prepared for analysis with EPANET Tookit version 2.2. The existing network has a number of control elements (isolation on/off valves, pressure control valves and flow control valves). The network also has a number of wells in which the pumping capacity is limited (Table 1). In addition, the capacity of the main reservoir is also limited (Table 1).

The participants must initially propose a suitable mode of operation that, in accordance with the capacities of the network, allows the largest possible number of users to be supplied for the longest possible time. In order to do so, they must configure the statuses of the individual network elements (valves, pumps, etc.). In other words, the initial positions of each of the elements must be decided and the moments in which a change in the position of these elements occurs must be indicated. The only valves installed in the model (control and isolation) are those defined in the Valves section. To close any line in the model it will be necessary to first install a valve.

This initial network proposed by each participant will be evaluated according to the criteria defined in the problem. In other words, not only the assessment of the network over the 5 years of the investment study, but also the assessment of the initial situation will be carried out.

3.4 On investments

The investments are made annually, and are concentrated on the first day of the year, with all the improvements made at the beginning of the year being operational throughout the year. The amount of money to be invested each year is fixed: **650 000 €/year**. This annual budget may not be exceeded at any time. The total period to be analyzed is 5 years.

Investments can be directed towards: detecting and repairing leaks, replacing sections of pipe, installing control or isolating valves, installing water meters, extending tanks or replacing well pumps. Each type of investment has an associated cost.

The investments can be used to carry out any of the following actions:

- Detecting and repairing leaks. The leaks will be known a priori, but each leak will have a detection cost and a repair cost associated with it.

- Completely replacing a pipe with a new one. It is not possible to install pipelines in parallel with the existing ones. When a pipe is renewed, the entire line of the model shall be renewed. It will not be possible to replace only a section of a line in the model.

- Install new valves in the network. There are two types of valves considered: isolation valves and control valves. Isolation valves do not introduce head losses and have only two positions (open or closed). Control valves can be of three different types: pressure reducing valves (PRVs), pressure sustaining valves (PSVs) and flow limiting valves (FCVs). For all control valves, the setting may vary throughout the simulation. The valves introduced (isolation or control) can be used to regulate the operation of the network or to define different sectors.

- Increase the capacity of the network tanks. There is a cost associated with tank expansion. Given space constraints, it will not be possible to increase the diameter of existing tanks to a value greater than twice that initially available. Neither the minimum nor the maximum level can be changed during tank expansion. The initial level shall be recalculated on the basis of the enlargement carried out in such a way that initially there is no more water in the tank than there was in the initial model.

- Replace existing borehole by others equal to the existing ones (and with better performance) or different from the ones currently installed.

- Install frequency inverters on existing pumps. Once the inverter is installed, the speed can be operated at speeds different from the nominal speed. The variation of the efficiency of the pumps at speeds different from the nominal speed shall be done using the correction proposed by Marchi and Simpson (2013).

3.5   On well pumping

The dynamic level of each of the wells is assumed not to vary throughout the simulation. This level is equal to the piezometric head of the reservoir installed immediately upstream of the pump. This reservoir represents the water level in the well.

All well pumps are defined by their best efficiency point (BEP), defined by the head H_0 and the flow Q_0. From this point all other pump characteristics are defined. The characteristic curve (H-Q) of the pump is given by the equation:

$$H = \frac{4}{3} H_0 \left(1 - \frac{Q^2}{4 \cdot Q_0^2} \right) \tag{1}$$

On the other hand, the curve (η-Q) indicating the efficiency of the pump as a function of the flow rate is given by the equation:

$$\eta = \eta_0 \left[2 \cdot \frac{Q}{Q_0} - \left(\frac{Q}{Q_0} \right)^2 \right] \tag{2}$$

where η_0 is the efficiency of the pump at its BEP. This value is 80% for every new pump and 65% for existing pumps.

The maximum operating flow rate of any pump shall never exceed the design flow rate of the pump (Q_0) by more than 50%. That is, the maximum flow that a pump can deliver is $1.5 \cdot Q_0$. The pumps can operate in continuous mode or stop at certain times. The run/stop status of these pumps shall be determined in each proposal by the participants. Pumps could also be replaced by more powerful pumps, but the maximum flow rate extractable from each well is limited (Table 1).

The models available for installation are shown in Table 2. In this table, the model C_XX/YY indicates that the height of the BEP is XX m, the flow rate YY l/s and the efficiency 80%.

Table 2. Pump models available for installation in wells.

H(m)	Q (l/s)								
	10	15	20	25	30	35	40	45	50
10	C_10/10	C_10/15	C_10/20	C_10/25	C_10/30	C_10/35	C_10/40	C_10/45	C_10/50
15	C_15/10	C_15/15	C_15/20	C_15/25	C_15/30	C_15/35	C_15/40	C_15/45	C_15/50
20	C_20/10	C_20/15	C_20/20	C_20/25	C_20/30	C_20/35	C_20/40	C_20/45	C_20/50
25	C_25/10	C_25/15	C_25/20	C_25/25	C_25/30	C_25/35	C_25/40	C_25/45	C_25/50
30	C_30/10	C_30/15	C_30/20	C_30/25	C_30/30	C_30/35	C_30/40	C_30/45	C_30/50
35	C_35/10	C_35/15	C_35/20	C_35/25	C_35/30	C_35/35	C_35/40	C_35/45	C_35/50
40	C_40/10	C_40/15	C_40/20	C_40/25	C_40/30	C_40/35	C_40/40	C_40/45	C_40/50
45	C_45/10	C_45/15	C_45/20	C_45/25	C_45/30	C_45/35	C_45/40	C_45/45	C_45/50
50	C_50/10	C_50/15	C_50/20	C_50/25	C_50/30	C_50/35	C_50/40	C_50/45	C_50/50
55	C_55/10	C_55/15	C_55/20	C_55/25	C_55/30	C_55/35	C_55/40	C_55/45	C_55/50
60	C_60/10	C_60/15	C_60/20	C_60/25	C_60/30	C_60/35	C_60/40	C_60/45	C_60/50
65	C_65/10	C_65/15	C_65/20	C_65/25	C_65/30	C_65/35	C_65/40	C_65/45	C_65/50
70	C_70/10	C_70/15	C_70/20	C_70/25	C_70/30	C_70/35	C_70/40	C_70/45	C_70/50
75	C_75/10	C_75/15	C_75/20	C_75/25	C_75/30	C_75/35	C_75/40	C_75/45	C_75/50
80	C_80/10	C_80/15	C_80/20	C_80/25	C_80/30	C_80/35	C_80/40	C_80/45	C_80/50
85	C_85/10	C_85/15	C_85/20	C_85/25	C_85/30	C_85/35	C_85/40	C_85/45	C_85/50
90	C_90/10	C_90/15	C_90/20	C_90/25	C_90/30	C_90/35	C_90/40	C_90/45	C_90/50

Two additional elements can be added to each of the pumps: a valve to control the flow rate and a frequency inverter to vary the pump speed. Any type of valve can be installed at the outlet of the pumps to limit the flow rate extracted from the well. Each of these valves will have an associated cost. A frequency inverter may also be installed on each of the pumps to convert them to Variable Speed Pumps (VSPs). The cost of installing the frequency inverter will be given by the power at the BEP.

3.6   On the supply sectors

One of the objectives of the challenge is to define the most appropriate initial operation of the installation. For this purpose, only the initially installed valves can be used. The distribution of the different sectors may change over time (year to year). For this purpose, the installed valves can be used, and the isolation valves can be replaced by control valves (PRVs, PSVs or FCVs). In addition to the valves that regulate the inlets to each sector, it is possible to install more isolation or control valves at other points in the network to control the system.

However, the opening and closing times of the valves feeding the different pre-set sectors can be modified according to the proposals of each participant. Ideally, in the optimal situation, all the supply valves of the sectors should remain open 24 x 7 h, only regulating the outlet pressure if necessary.

3.7   About the hydraulic simulation

The operation of the network is the same for all 52 weeks of the year. However, it will change from year to year depending on the investments made and the changes in the way the network is controlled.

The desired weekly demand of the population does not change throughout the study period. However, it does vary over the 168 h of a week. The weekly pattern of the desired demand is the same for all nodes. However, the base demand changes from node to node. The supply of the desired demand is not guaranteed and deficit periods may occur. The number and location of leakages also does not grow over the whole period. However, the intensity of leakage grows exponentially over time, if not repaired.

To simulate the hydraulic behavior of the network it is proposed to use the EPANET Toolkit 2.2 as a base solver, although any other simulator or commercial software is supported, including free surface simulators. The simulation software used should include the declaration of pressure-dependent demands. In any case, all transient states caused by shift changes in the operation of the different sectors, or in the feeding of the reservoirs, shall be neglected.

The recommended simulation time step with which the solutions presented by the participants will be analyzed will be 1 hour. Participants may use different time steps if they wish, but all solutions will be evaluated with the EPANET 2.2 Toolkit and a time step of 1 hour.

4   MODELLING NETWORK ELEMENTS

4.1   LEAKAGE MODELLING

The current leakage in the network is provided as a baseline. The leaks are declared as point events, indicating their exact location along the pipes. The leaks will be simulated as emitters in EPANET, according to the law

$$q = k \cdot p^{\alpha}, \tag{3}$$

where q is the leaked flow and p is the pressure at the point where the leak is located. The importance of each leakage is determined by the emitter coefficient k, different for each node, and the exponent α (equal to 1 for all nodes).

Unrepaired leaks shall be assumed to grow exponentially with time. The value of the coefficient k, according to the expression

$$k = k_0 \cdot e^{0.25 \cdot \frac{w}{260}}, \tag{4}$$

where k_0 is the initial value of the k coefficient, and w is the number of weeks since the start of the work. Leakage growth throughout the year will be assumed not to affect the hydraulic behavior of the network from

week to week. That is, the value of the coefficient k for each unrepaired leak will be updated at the beginning of each year and will remain constant for the 52 weeks of the year.

The position and the value of the coefficient k_0 of all leakages are detailed in the file Leakages.xls. As an example, a part of this file is shown in Table 3.

Table 3. Leakages position and value data

Link	Length from the initial node (m)	Coef. k_0
L343	67.36	0.000561
L343	56.97	0.000511
L344	17.04	0.000012
L345	37.70	0.000438
L588	9.74	0.000100
L588	6.81	0.000101
L10	123.94	0.001481
L10	117.32	0.001458
L1009	26.48	0.026943
L1010	22.43	0.000548
L1022	46.11	0.000837
L1079	47.28	0.000194
L1085	15.13	0.000783
L1085	29.37	0.000730

To simulate each leak, it is advisable to declare a new node at its location in the pipe, determining its elevation by interpolation between the values of the extreme nodes of the pipe. Alternatively, other methods of representing leakage (e.g. concentrated at pipe end nodes) can be used. In any case, the model used to evaluate the solutions submitted by the participants will be the one that defines the intermediate nodes in each pipe. Note that negative pressure at a point where a leak is present must be prevented from causing water to enter the system.

Once a leak has been repaired, it is assumed that it will never appear again. It is assumed that no new leakage will occur during the 5-year study period.

4.2   MODELLING OF DOMESTIC TANKS

The full network model would represent the behavior of all domestic tanks. This involves the dynamic integration of the continuity equation over thousands of small tanks, which would result in an incredible increase in computational time.

Alternatively, in this problem, the behavior of the users will be represented as pressure-dependent demands, as described in the EPANET Toolkit 2.2. Specifically, the representation of the demanded consumption at a node i ($q_{D,i}$) will be given by the expression (Wagner et al., 1988):

$$q_{D,i} = \begin{cases} D_i & p_i \geq p_f \\ D_i \left(\dfrac{p_i - p_0}{p_f - p_0} \right)^e & p_0 < p_i < p_f \\ 0 & p_i \leq p_0 \end{cases} \tag{5}$$

where p_i is the head pressure available at the node, D_i is the full normal demand at node i when the pressure p_i equals or exceeds P_f, P_0 is the pressure below which the demand is 0, and e is a pressure function exponent usually set equal to 0.5 (to mimic flow through an orifice).

The idea behind the proposed model is as follows. When the pressure in the network is lower than P_0 it is not possible to fill the tanks, so given the low capacity of the tanks, consumption cannot be satisfied. Therefore in these circumstances the demand delivered to the user will be zero. In the event that the pressure in the network is higher than P_f, it will be possible to supply all the demand requested by the user. At such times, enough pressure is available to keep the household tanks full. The behaviour is somewhat more complex in the case where the pressure in the network is between P_0 and P_f. In this case it is assumed that the network consumption will be that given by Wagner's expression. Assuming an exponent e of value 0.5 and that the minimum pressure value P_0 is 0, the expression proposed by Wagner means admitting that the resistance in the section between the consumption node and the domestic tank has a resistance equivalent to that which would cause a flow rate D_i when the pressure in the network is P_f.

For all consumption nodes the following parameters shall be considered fixed:

- $p_0 = 0$ m

- $p_f = 10$ m

- $e = 0.5$

Only the demand D_i will vary from node to node.

The values p_0 and p_f are necessary to define the functioning of the pressure-dependent consumption model that is used to represent the behavior of the users. However, the local by-laws of the supplied municipality consider p_{ref} = 20 m as the minimum acceptable pressure to consider a quality supply.

4.3   MODELLING OF SUPPLY SOURCES

The network was originally designed to be gravity-fed from a single reservoir. This was fed from a source whose average flow was sufficient to cover the needs of the population. However, the increase in demand with the appearance of leaks, the incorporation of new users and the installation of domestic tanks meant that the capacity of the main source was insufficient, forcing new boreholes to be drilled to meet the increase in demand.

Finally, as there were no more water resources, and given the difficulty of repairing leaks and regulating demand at all consumption points, it was decided to limit the flow injected from the different sources by throttling their outlet connection to the network by means of a valve. In the initial EPANET model of the network, this valve has been represented as an FCV whose setting is equal to the maximum flow rate that can be provided by the source. In the case that the network does not reach the maximum flow rate demanded by the source, the valve will be completely open. In case the demand of the network is higher, the valve will close to limit the supply. In this case there may be significant negative pressures at the outlet of the valve. These pressures represent the air inlet through the suction cups and the operation of the pipeline as a free surface flow.

Likewise, the flow rate drawn from the wells can also be limited by control a valve at the outlet of the pump, which can also cause negative pressures.

In a simulation using a model designed to work under pressure, such as EPANET, it will be interpreted that the air enters the areas with negative pressure through air valves. It shall be accepted that the entry and expulsion of air from the pipes is instantaneous, without causing problems in the installation.

4.4   MODELLING WATER SUPPLY SECTORS

Another way of limiting demand is to establish an intermittent supply in shifts, where in each turn the needs of one or more hydraulic sectors are served. For this purpose, the study network could be divided into supply sectors. Each sector is isolated from the others, and maintains several inflow points. In addition, a backbone network keeps all sectors connected to each other and to the supply sources.

Inlets to the sectors are controlled by isolating valves, which are supposed to open and close instantaneously. In any case, these valves can be replaced by other control valves. As many isolation or control valves as necessary can be installed to define the sectors.

Transients are not taken into account, so that the opening of the valve in a sector means the immediate arrival of water to all the consumption points in that sector. In the same way, closing a valve means the immediate cancellation of the supply.

The current clustering of the network in different sectors has not been defined. The times at which the valves delimiting the sectors are open or closed are also not predefined. The participants will have to make the division of sectors they consider appropriate according to the existing valves in the network. They will also have to program the valve operating times to manage the network's intermittent operation shifts.

The addition of new valves (isolation or control) to the network may be done in the first year of investments (not in the initial situation). Each of them will have an associated cost depending on the size and type of valve.

5   COST ESTIMATION

Each action that can be taken on this problem has an associated cost. The following sections describe the costs associated with each of these actions.

5.1   Cost of detecting and repairing a leak

The cost of repairing a leak depends on two factors: the size of the leak and the diameter of the pipe in which the leak occurs. The expression to be used for the calculation of this cost is

$$C_{repair} = [94 - 0.3 \cdot D(mm) + 0.01 \cdot D(mm)^2] \cdot [1.5 + 0.11 \cdot \log_{10}(k)] \qquad (6)$$

where C_{repair} is the repair cost (in € and rounded to two decimal places) of a leak of value k (with flow in l/s and pressures in metres) in a pipe of diameter D(mm).

The cost of leak detection varies inversely with the size of the defect. That is, smaller leaks will have a higher detection cost, while larger leaks will have a lower detection cost. The cost function to be used to calculate the cost of detection is

$$C_{det} = 2400 \cdot e^{-28 \cdot k} \qquad (7)$$

Finally, the final cost associated with the elimination of a leak is the sum of the cost of detection and the cost of repair:

$$C_{leak} = C_{det} + C_{repair} \qquad (8)$$

Although the distribution of the leaks and their magnitude are provided in the starting data, it is assumed that the manager does not know them a priori, having a detection cost that is decreasing with the magnitude of the leak, and a repair cost that is increasing with the magnitude of the leak.

5.2   Cost of replacing a pipe

The replacement cost of a pipe will depend on the diameter of the pipe. The function that represents this cost is

$$C_{rep} = A_{rp} + B_{rp} \cdot D + C_{rp} \cdot D^2 \qquad (9)$$

with C_{rep} is the replacing cost in €/m and D is the diameter of the pipe in m. The values of the cost function A_{rp}, B_{rp} and C_{rp} have been obtained by adjustments from the pipe installation cost data: (A_{rp} = 13; B_{rp} = 29; C_{rp} = 1200). The inside diameters of the pipelines that can be installed to replace the existing ones are shown in Table 4.

Table 4. Available pipe diameters and their costs.

D (mm)	50	63	75	100	125	150	200	250
C_{rep} (€/m)	17.45	19.59	21.93	27.9	35.38	44.35	66.8	95.25
D (mm)	300	350	400	450	500	600	700	800
C_{rep} (€/m)	129.7	170.15	216.6	269.05	327.5	462.4	621.3	804.2

Under no circumstances may an existing pipe be replaced by a smaller diameter pipe. If it is necessary to reduce the carrying capacity of a pipeline, a valve must be installed.

5.3 Cost of increasing the volume of the tanks

One of the investment actions is the expansion of existing tanks. This expansion has a cost associated with it, which is a function of the volume of the tank to be expanded. The function is

$$C_{tank} = 2000 + 200 \cdot \Delta \forall \tag{10}$$

where C_{tank} is the cost of increasing the capacity of the tank in € and $\Delta \forall$ is the increase in volume, in m^3.

It should be noted that the expansion of a tank cannot result in an increase in its initial capacity. Therefore, in the case of increasing the tank capacity, its initial level will be recalculated so that the volume of water contained in it is equal to that of the tank defined in the initial EPANET file.

5.4 Cost of installing valves

It is possible to install valves in all defined pipelines defined in the model. The cost associated with the installation of a valve is given by equation

$$C_{valve} = A_v \cdot D^{B_v} \tag{11}$$

where C_{valve} is the cost of installing a new valve in €/unit, D is the diameter of the valve in m and A_v and B_v are characteristic coefficients of the cost curve that depend on the type of valve (Table 5). In any case, the diameter of the new valves will always be one of the diameters defined in Table 4 for pipes.

Table 5. Value of coefficients A and B for different types of valves.

Valve Type	A_v	B_v
Isolation	99000	2.16
PRV	260000	2.1
PSV	265000	2.1
FCV	275000	2.1

5.5 Cost of replacing a well pump

The cost of installing a pump in a well will have two different terms: the cost of extracting the installed pump (C_{ex}) and the cost of installing the new pump (C_{np}).

$$C_{pump} = C_{ex} + C_{np} \tag{12}$$

The cost of removing the installed pump and installing a new pump is calculated as a function of the depth at which the pump is located. This depth is the difference between the water level in the well (Table 1) and the level at the point immediately downstream of the pump. This cost is estimated at 500€ per meter of difference the elevation of this two points (water level and pump outlet). In the case of installing a pump that does not draw from a well, this cost will not be taken into account.

The installation cost of the new pump is calculated from the power (P_{BEP}) in the BEP.

$$C_{np} = 1475 \cdot P_{BEP}^{0.525} \tag{13}$$

where C_{np} is the cost of installing a new pump and P_{BEP} is the power at the BEP of the installed pump in kW.

5.6 Cost of installing frequency inverter

The cost associated with the installation of a frequency inverter depends directly on the power of the pump at its BEP. The cost including the installation of the inverter and the electrical adaptation of the system (C_{inv}) is given by the expression

$$C_{inv} = 1350 + 235 \cdot P_{BEP} - 1.2 \cdot P_{BEP}^2 \tag{14}$$

whare C_{np} is the cost of installing the inverter and P_{BEP} is the power at the BEP of the installed pump in kW.

Once the frequency inverter has been installed, the pump can be adjusted to run at speeds different from the rated speed. In no case may a pump operate at speeds higher than the rated speed.

6   SERVICE INDICATORS

Each participant has to present six different operating scenarios: the initial situation (corresponding to the first year in which no investments are made) and the situation after investments are made in the following five years. In each of these six scenarios, the effectiveness of the actions proposed by the participants will be assessed.

In short, the assessment of each solution requires consideration of the analysis of what has happened over 6 years. The first year starts without being able to make any investment, but it is possible to adjust the operation mode of the network (definition of the operation of pumps and valves). From that point onwards, investments are made each year, which will be available at the beginning of the following year. In other words, an investment plan is made in five stages. After each stage, the performance of the network during that year is analysed.

The indicators considered for this purpose are described below.

6.1   Indicator I_1: proportion of the number of effective hours a subscriber is served

Indicator I_1 reflects the proportion of the number of effective hours that a subscriber has service available over the 6 years.

$$I_1 = \frac{\sum_{j=1}^{6} \sum_{i=1}^{N} n_{i,j}}{N \cdot 24 \cdot 364 \cdot 6} \tag{15}$$

where N is the total number of subscribers (nodes with demand), and $n_{i,j}$ is the total number of hours per year the node i has service ($P > P_0$) during the scenario j. Its value ranges from 0 to 1.

6.2   Indicator I_2: Proportion of subscribers with continuous service

The second indicator I_2 reflects the proportion of users with continuous service over the 6 years,

$$I_2 = \frac{\sum_{j=1}^{6} \sum_{i=1}^{N} w_{i,j}}{N \cdot 5} \tag{16}$$

where $w_{i,j}$ is 1 if user (node) i has had continuous service in year j, and 0 otherwise. Its value also ranges between 0 and 1.

Logically, if I_1 is 1, then I_2 is also 1, and vice versa, but while the first indicator measures the degree of user satisfaction, the second measures the effectiveness of the measures taken from the point of view of the objectives pursued.

6.3   Indicator I_3: volume of water leakage

The third indicator I_3 reflects the total volume of water leaked from the network after 6 years, referred to the total volume of water supplied, and is expressed as:

$$I_3 = \frac{\sum_{j=1}^{6} \sum_{\ell=1}^{L_j} V_{\ell,j}}{\sum_{j=1}^{6} \sum_{s=1}^{S_j} V_{s,j}} \tag{17}$$

where $V_{l,j}$_is the volume lost by leakage l in year j, L_j is the number of active leakages in the same year, $V_{s,j}$ is the volume supplied by source s in year j, and S_j is the number of active sources in year j. Its value also ranges between 0 and 1. A value of 0 would mean no leakage after the first year's actions, while a value of 1 would mean that all the flow supplied is lost, with no water being received by the users during the whole period.

6.4 Indicator I₄: proportion of volume of water supplied to users

The fourth indicator I_4 is related to the previous one, but measures the volume of water required by subscribers that could not be supplied after 6 years. It is expressed as:

$$I_4 = \frac{\sum_{j=1}^{6} \sum_{p=1}^{N} V_{i,j}^s}{\sum_{j=1}^{6} \sum_{d=1}^{N} V_{i,j}^d} \tag{18}$$

where $V_{i,j}^s$ is the volume actually supplied to user i during year j, and $V_{i,j}^d$ is the volume demanded by user i during year j, and N is the total number of users (or nodes with demand). Its value also ranges between 0 and 1. A value of 0 would mean that no demand would be satisfied and a value of 1 would mean that all demands would be satisfied after the first year's actions. Let us note that all demands can be satisfied, but with a high volume of leakage in the network, which would also be unsatisfactory. Thus, indicator I₃ is complementary to I₄.

6.5 Indicator I₅: Level of pressures at consumption nodes

The fifth indicator I_5 measures the level of pressures available at the consumption nodes over the rehabilitation period, which is another way of reflecting the effectiveness of the measures taken. This level of effectiveness of the pressure supply is measured with respect to the reference pressure p_{ref} defined by the local by-laws. Mathematically it is defined as

$$I_5 = \frac{\sum_{j=1}^{6} \sum_{h=1}^{168} \sum_{i=1}^{N} p_{i,h,j}}{168 \cdot 52 \cdot 6 \cdot p_{ref}} \tag{19}$$

where $p_{i,h,j}$ is the pressure at node i and hour h of year j, expressed in m. Only nodes i with demand are considered, whose total number is N. Moreover, 168 are the hours of a week, since weeks are repetitive within the same year (52 weeks). In order to avoid the nodes with high pressures can distort the mean pressure values, in those cases where the value of $p_{i,h,j}$ is higher than p_{ref}, the value of $p_{i,h,j}$ in equation (19) shall be taken as p_{ref}. Therefore, the definition of the I_5 indicator can be expressed as

$$I_5 = \frac{\sum_{j=1}^{6} \sum_{h=1}^{168} \sum_{i=1}^{N} min(p_{i,h,j}, p_{ref})}{168 \cdot 52 \cdot 6 \cdot p_{ref}} \tag{20}$$

Its value will range from 0 to a higher value of 1 when the average pressures in all nodes are above p_{ref}.

6.6 Indicator I₆: Percentage of users supplied continuously

The sixth indicator I₆ determines the percentage of users who can finally be supplied directly from the network on a continuous basis. This requires the pressure at the junction is greater than p_f at all times. It is defined as:

$$I_6 = \frac{\sum_{j=1}^{6} \sum_{i=1}^{N} \delta_{i,j}}{6 \, N} \tag{21}$$

where $\delta_{i,j}$ is 1 if at node i $p_{h,i,j} > p_{min}$ for $h = 1 ... 168$, i.e. for all the hours of the week, and therefore of year j, is satisfied. Otherwise, it will be 0. Note that this condition can be met only from a certain year onwards, and is more restrictive than the continuous supply condition reflected by I₂, where no minimum pressure limits are set, and less restrictive than the minimum pressure requirement p_{ref} reflected by I_5.

6.7 Indicator I₇: Pipe length with negative pressures

The seventh indicator I_7 determines the total length of pipe subjected to depressions during the whole period, which is supposed to be avoided by the air inlet in the pipes. It is expressed as:

$$I_7 = \frac{\sum_{j=1}^{6} \sum_{m=1}^{M} L_{m,j}}{6} \tag{22}$$

where $L_{m,j}$ is the longest negative pressure length of pipe m in year j. This maximum value of the length of pipe subjected to depression is obtained by analyzing the values of this length in each of the 168 instants of time calculated. A depression is considered to be present when the simulation result shows a value of $p<0$ in all or

part of the pipe. If at both ends $p<0$, the whole pipe is considered to be depressed. If $p<0$ only at one end, the proportional part under depression is determined by linear interpolation.
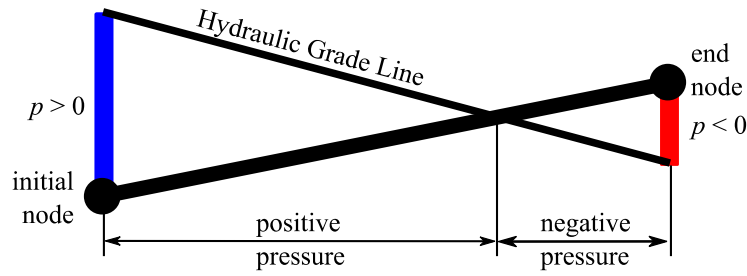

Figure 1. Linear interpolation of pipe length with negative pressure.

This parameter is much more significant if it is expressed in meters, than if it is relativized to the total length in pipes of the network, so that its value will always be ≥ 0, being limited only by the total length of the network. It has only been relativized with respect to the total number of years considered, so that it is not an accumulative value.

To take this term into account, the pipe must be in active service. Pipes in sectors without service are not counted.

6.8 Indicator I_8: Energy consumption of pumps in operation over the whole period

The eighth indicator I_8 takes into account the total energy consumption of the pumps in operation over the whole period. It is determined as:

$$I_8 = \sum_{j=1}^{5} \sum_{p=1}^{P} E_{p,j} \tag{23}$$

where $E_{p,j}$ is the energy consumption of pump p over year j, expressed in kWh, and P is the total number of pumps in the network. Since there is no reference for maximum energy consumption, this indicator shall also be expressed in absolute units. Its value will always be ≥ 0, and may reach the ideal case of a value of 0 if it is not necessary to activate any of the booster pumps.

6.9 Indicator I_9: Level of equity in supply

The last indicator I_9 reflects the level of equity in water supply to different subscribers. For this purpose it is proposed to use the indicator proposed by Gottipati and Nanduri (2014), which is expressed as:

$$I_9 = 1 - \frac{ADEV}{ASR} \tag{24}$$

with

$$SR_{ij} = Supply\ Ratio = \frac{V_{ij}^s}{V_{ij}^d} \tag{25}$$

$$ASR = Average\ Supply\ Ratio = \frac{\sum_{j=1}^{6} \sum_{i=1}^{N} SR_{ij}}{6N} \tag{26}$$

$$ADEV = Average\ Deviation = \frac{\sum_{j=1}^{6} \sum_{i=1}^{N} |SR_{ij} - ASR|}{6N} \tag{27}$$

where V_{ij}^s is the volume actually supplied to user i during year j, V_{ij}^d is the volume demanded by the same subscriber in year j, and N is the total number of users (or nodes with demand). If all users receive the demanded volume, then $ASR = 1$, taking a value less than 1 when the network is deficient. Note that the definition of ASR is similar to that of the I_4 indicator, although not exactly the same. But if the ratio is the same for all users, then

$ADEV = 0$ and $I_9 = 1$, which would be the ideal value. Since the average deviation cannot exceed the mean value, the minimum value of I_9 will be 0.

7 EVALUATION OF THE PROPOSALS

Participants must submit:

- The operation of the initial network without making any investment (use template file).

- The detail of the investments made each year (use template file).

- The operation of each of the network elements in each simulation of 168 hours performed in each of the five years.

- The participants will deliver six INP files (on for the initial configuration of the network and one for every year considered). Each file should contain the proposed improvements, and the actions to control the network during a total simulation period of one week.

The control actions to regulate the operation of the network, both for the initial model and for the five years of study are:

- Hourly control actions

- Actions based on Simple Controls of the EPANET Toolkit 2.2

- Rule-Based Controls of the EPANET 2.2 Toolkit will not be allowed.

The evaluation of the participants' solutions will be carried out as follows:

- In order to evaluate the effect of the improvements introduced each year, the team responsible for the challenge will carry out a simulation from the INP file provided, using its own software, based on the EPANET Toolkit, which reproduces all the conditions and working hypotheses mentioned above.

- All participants will be verified to comply with the following restrictions:

    o The limits imposed on the extractable flows from each source of supply must not be exceeded.

    o The annual investments shall not exceed the set budget.

- Once the restrictions have been verified, the following values will be determined:

    o The actual percentage of hours that each subscriber is supplied, over the whole period, shall be kept to a maximum.

    o The number of users with continuous service at the end of each year shall be a maximum.

    o The volume leakage in the network, at the end of the whole period, shall be minimal.

    o The proportion of the volume of water supplied to users should be maximal.

    o The average level of pressures, weighted to all users, shall be at a maximum.

    o The percentage of users supplied continuously shall be a maximum.

    o The pipe length with negative pressures should be kept to a minimum.

    o The energy consumption of the pumps over the entire period should also be kept to a minimum.

    o Finally, the equity of supply between all users will be assessed, i.e. the distribution of the deficits between all of them, the ideal being to obtain maximum equity.

- Associated with these criteria, the indicators listed in the previous section have been declared, which provide a numerical value associated with the degree of compliance with these criteria.

- The solution of each participant will be standardized with respect to each of the criteria, with a value of 1 for the participant with the best score and 0 for the participant with the worst score. The valuation of the rest of the participants will be made linearly between 0 and 1 according to the value of each criterion.

- The score of each participant will be the sum of the standardized scores obtained for each criterion. The participant with the highest score will be the winner of the challenge.

Finally, it should be noted that there are some restrictions for participation in the challenge:

- The same research group will not be allowed to submit two participating teams.

- No participant may belong to any of the research groups of the Battle Organizing Committee.

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