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TOWARDS ECO-LAYOUTS IN WATER DISTRIBUTION SYSTEMS

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TOWARDS ECO-LAYOUTS IN WATER DISTRIBUTION SYSTEMS

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ABSTRACT

To achieve maximum efficiency in water-pressurized transport it is necessary to perform a global analysis, whenever possible starting from the system's conception. The first stage of the process is the network layout, the main topic of this paper. And the optimum topology from an energy point of view (or eco-layout) is the one that, insofar as is feasible, allows equalizing the network's pressure to the set pressure standards. Eco-layouts can be easily designed in new systems but are difficult to implement, mainly in the short-term, in operating networks. Nevertheless, as no system is eternal, the required actions can be gradually implemented. Therefore, the main goal of this paper is to identify and discuss these guidelines and actions, some apparently contradictory to current design criteria, whereas others endorse modern management trends. These strategies can be summarized in two points: Firstly, providing lower pressure to consumers saves energy. Secondly, setting up smaller pressure zones in terms of the elevation steps between zones will

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enable water companies to supply water at lower pressure in hilly areas. In the end, in networks with more efficient layouts, important energy savings can be achieved.

INTRODUCTION

In developed countries, water pressurized transport is now responsible for up to 6% (WW, 2013) of the electricity used, while pressurized irrigation systems in Spain consume 3% of the total energy (Corominas, 2010). And because there is a growing need to transport water from where it is to where it is required, strong economic and environmental reasons advise reducing these energy requirements as much as possible. To achieve this, more efficient systems are needed, a broad concept that includes a wide array of measures. From demand management actions (reducing leaks and consumption) to more efficient pumping stations. Nevertheless, reaching maximum efficiency values is only possible through a global analysis, starting with the network layout, the main objective of this paper. The optimum topology from an energetic point of view (or eco-layout) is the one that, insofar as is feasible, allows equalizing the network's pressure to the pressure the standards set. This is an ambitious approach summarized in a word, "ecodesign". Indeed, according to ISO 14006 "*Ecodesign can be understood as a process integrated within the design and development that aims to reduce environmental impacts and continually to improve the environmental performance of the products, throughout their life cycle from raw material extraction to end of life*". It is worth noting that "*in this International Standard, the term product is understood to cover both goods and service*s" (ISO, 2011). An alternative ecodesign definition is "a preventive approach, designed to optimize the environmental performance of products, while maintaining their functional qualities, and providing genuine new opportunities for manufacturers, consumers and society as a whole" (EP, 2009).

The first stage of a water network ecodesign process, i.e. defining its topology, has not received the attention it deserves. In the layout conception, three goals have prevailed to date: complying with quality standards, maximizing reliability and minimizing investment. Nevertheless the energy aspects, although dealt with in depth once the layout has been defined, have largely been ignored in the initial design stage. In operating systems, diagnostics (Cabrera et al., 2014), audits (Cabrera et al., 2010), metrics (Pelli and Hitz, 2010), pumping operation and optimization (Price and Ostfeld, 2014), demand management impacts (Ghimire and Barkdoll, 2010) and even energy recovery (Fontana et al., 2012) are matters that have been thoroughly tackled. Nevertheless, only on few occasions (Gómez et al., 2015) has the permanent energy impact of the layout, the objective of this article, been analyzed.

Last, it is important to underline the difference between optimal layout and ecolayout. In the first case the objective is to minimize the economic cost of the network, and mainly applies to irrigation uses, tree networks, in which reliability is not a priority (Bhave and Lam, 1983). However, the objective of the ecolayout is to minimize the energy requirements.

To highlight the importance of this first step of the ecodesign, and to outline the path towards eco-layouts, this paper is organized as follows:

- Discussion of the basic principle of the eco-layout, i.e., to equalize (as far as possible) the network's pressure to the pressure the standards set.
- Analysis of the topographic energy concept and its role as a layout energy efficiency metric.
- Analysis of eco-layout strategies and their comparison with current water network management actions.
- Protocol to minimize energy requirements in water networks.

ENERGY MANAGEMENT AREAS, THE ECO-LAYOUT BASE

Energy losses in water distribution systems can be classified in two groups. Operational losses, widely discussed in literature (Cabrera et al., 2010), are inherent to the system´s operation. Energy lost in leaks, inefficient pumping, friction in pipes, avoidable excesses of delivered energy to users and other types of losses, such as break pressure in private storage tanks are all operational losses. These losses are often high in practice and thus need careful attention by management (in an ideal system these losses should be zero). On the other hand we call structural losses (independent of management) those that are related to the topology of the system. In fact they can only be reduced by modifying the topology of the network. This paper explores ways to reduce these losses because, there can be no question, supplying water at higher pressure than needed is a waste of energy. The topographic energy inherent to irregular profiles (Figure 1) cannot be minimized easily. But this is not the case of many fairly common systems such as the one depicted in Figure 2.

To focus our analysis on the topographic energy (i.e. structural losses), the system is assumed to be ideal (no operational losses) an hypothesis that, for the sake of clarity, we assume in the whole paper because in real systems the conclusions are the same. The next section is the only exception, because it is necessary to include friction losses in order to prove the strong correlation between the different sources of energy and the structural losses.

Fig. 1. Topographic energy concept in an ideal system (from Cabrera et al., 2014). (Figure not to scale)

Subdividing water networks into energy management areas (EMA) is the key strategy towards eco-layouts. As we will see in the next example, in a coupled (Figure 2) or decoupled (Figure 3) system, the required energy largely depends on this fact. If the same level of operational inefficiencies (pumping, friction, leaks,..) apply to both systems, the total energy required will be proportional to the baseline line (structural losses) in both ideal cases. And obviously, the lower, the better.

Fig. 2. Ideal system simultaneously supplying two zones located at different levels.

Let us therefore, determine the energy baseline for both systems (the standard pressure is 20 m). Following the established terminology (Cabrera at al., 2014), the minimum useful energy to deliver to users, E_{uo}, is:

$$E_{uo} = \gamma \sum v_j \left[\left(z_j - z_l\right) + h_{o,j}\right] =$$
$$= \gamma[(0.02\Delta t[(70-0)+20]) + (0.08\Delta t[(20-0)+20])] = \gamma 5\Delta t\, Joules \tag{1}$$

where γ is the specific weight; v_j the volume delivered at the generic node j (at height z_j); z_l the lowest point in the system (with positive or negative consumption) and $h_{o,j}$ the standard pressure in the node j. In Eq. 1, the two header nodes represent the areas to be supplied. On the other hand the ideal topographic energy, i.e., the structural losses, E_{ti}, is the difference between the total energy supplied and the minimum energy required by users, which is equal to:

$$E_{ti} = \gamma \sum v_j \left(\left(z_h + h_{o,h}\right) - \left(z_j + h_{o,j}\right)\right) =$$
$$= \gamma\left[(0.02\Delta t\left((100+0) - (70+20)\right) + 0.08\Delta t\left((100+0) - (20+20)\right)\right] = \gamma 5\Delta t\, Joules \tag{2}$$

where z_h is the highest point (in this case the elevated tank), $h_{\mathrm{o,h}}$ the standard pressure at this point (zero in this case), and $h_{o,\mathrm{j}}$, the standard pressure in the node *j* (20 m). Therefore, the supplied energy, E_{si}, is:

$$E_{si} = \gamma V H_{hi} = \gamma(0.08 + 0.02)\Delta t 100 = \gamma \sum v_j \left[\left(z_j - z_l\right) + h_j\right] = E_{uo} + E_{ti} =$$
$$= \gamma 10\Delta t\, Joules = \gamma(5+5)\Delta t\, Joules \tag{3}$$

where V is the total volume injected into the system in an interval of time Δt, and H_{hi} the specific energy required without any inefficiencies. Whereas the ideal performance of the system, η_{ai}, is the relation between the useful, E_{uo}, and the supplied, E_{si}, energies (Cabrera et al., 2014), we obtain:

$$\eta_{ai} = \frac{E_{uo}}{E_{si}} = 1 - \frac{E_{ti}}{E_{si}} = 1 - \theta_{ti} \tag{4}$$

Therefore, in the energy balance θ_{ti} is the relative weight of the structural losses, i.e., the layout efficiency metric. In fact only when $\theta_{ti} = 0$, the ideal performance of a system could be one. Eq.

4 proves that, even without operational losses, the efficiency of the system is limited by the structural losses which, moreover, carry inherent problems (such as excesses of pressure). In our case:

$$\theta_{ti} = \frac{E_{ti}}{E_{si}} = \frac{\gamma 5 \Delta t}{\gamma 10 \Delta t} = 0.5 \quad (5)$$

With the ideal performance being the quotient between the supplied and the required energy equal to:

$$\eta_{ai} = 1 - \theta_{ti} = 0.5 \quad (6)$$

In real systems this value will inevitably be reduced by the operational losses. Only by carrying out structural refurbishment (Figure 3), i.e., decoupling the system in two subsystems, can this theoretical efficiency be improved.

Fig. 3. Ideal decoupled system (two subsystems).

The new energy balance is summarized in Table 1. The higher subsystem (Fig. 3) conserves the topographic energy, whereas in the second it is zero. The final result evidences the improvement: the ideal overall performance, $\eta_{ai,g}$, increases up to 96%, as a result of the decrease in topographic energy (from 50% to 4%), a reduction directly transferred to the injected energy, resulting in an energy saving equal to $\gamma 4.8 \Delta t$ $(= \gamma 10 \Delta t - \gamma 5.2 \Delta t)$. To reach 100% we would have to lower the height of the upper tank to 90 m.

Table 1. Energy balance of the ideal decoupled system (Figure 3)

This example proves that to avoid "structural losses" it is necessary to design systems that only deliver the required energy. This is an Utopian objective which, depending on the system's energy source, can be achieved to a greater or lesser.

TOPOGRAPHIC ENERGY MANAGEMENT AND SOURCES OF ENERGY.

Topographic energy can only be reduced by modifying the design of the system. Until now any surplus has been removed by dissipating any excess through pressure relief valves (PRV) or, better still, substituting them for Pumps as Turbines (PAT) to, whenever possible, recover that energy (Fontana et al., 2012). A lot of attention is being given to this relatively new strategy, driven by the growing climate change concern. Nevertheless, it is likely better in many contexts to reduce topographic energy through the layout of the system itself. Figures 2 and 3 illustrate an overview of the three actions. Fitting a PRV in the lower network is a fairly commonly used solution, or, where viable, resorting to the improved solution (PAT). But, indeed, the optimum solution is changing the layout of the system (see Figure 3). Hence, from an energy point of view, the logical order of actions is reduce, recover and remove, as Figure 10 summarizes. Three actions, three "Rs" which are reminiscent of the hierarchy of the Rs inherent to waste water management (reduce, reuse, recycle).

A more in-depth discussion about topographic energy management and its relationship with the different sources of energy require friction losses in the system to be included (this is the only exception in this conceptual paper, as it is mainly considering systems as ideal). Indeed, in real systems supplied by tanks, a rigid energy source (RES) cannot meet the exact needs because demands vary over time and, consequently, so do head losses.

If the height is established to meet the service standard during peak consumption hours, there will be an excess of energy in the off-peak hours, an excess that is currently dissipated using pressure relief valves (PRV). The energy rigidity of the tanks can only be slightly mitigated with variations in the surface water level.

In real systems to equalizing supplied and required energy with variable energy sources, VES, (parallel pumps fitted with variable speed drivers) is easier. Therefore, this is the only way to minimize the structural losses. For a 10 km distance between the potable water treatment plant and the network, Figure 4 shows the heights H_i needed depending on the source (variable, p_{iP}, rigid, p_{iT}), on the flow rate and on the pressures at the entrance to the network. As can be seen, VES permit equalizing pressure, whereas RES does not. It is worth emphasizing that this simple principle of the eco-layout design is impossible to be fully achieved in irregular topographic areas, although approaching it would be more feasible with VES.

Fig. 4. Supply with VES, equaling the required pressure and the supplied pressure.

In any case, as seen before, the fundamental action to balance injected and required pressures is to decouple, which is a strategy that, although there may be different objectives, has become more frequent with time. In particular DMA (District Metered Areas) for better leakage management and PMA (Pressure Management Areas) to minimize and reduce pressure oscillations. But the process actually follows a bottom - up approach. Operating networks are sectorized in DMA with a clear objective, to reduce leaks while hydraulic performances are maintained (Laucelli et al., 2017). If sectorization is tackled in a top-down approach (from the design stage), in addition to the undeniable benefits this entails (less breakages, reduced leakage, etc.), the energy saving is a remarkable added benefit.

OPTIMUM NETWORK LAYOUT. A CASE STUDY.

The aim of the following example is to show how to minimize the topographic energy in an irrigation network. Figure 5 shows the dimensions, consumption nodes (10 l/s constant in time and 20 m pressure), and elevations. The grids are equal (all sides, 1 km). The water to be distributed is stored in a big reservoir (elevation, 20 m) located in the center of the network. The system is ideal and operates 1500 h/year. The simplified branched network layout permits synthesizing the results. The analysis relates topographic energy, annual capital and the operational costs of three different layouts (Figures 5 and 6). Pump P_1 supplies the energy required at the highest nodes, and therefore an unavoidable surplus will be delivered to the others. With a suction level of 20 m (natural energy contribution), the height of the pump is H_p = 40 m.

The flow rate, the result of multiplying the number of nodes (80) by the unitary demand, is Q_p=800 l/s.

The ideal energy supplied, E_{si}, sum of natural energy E_n, and pumped energy E_p, and efficiencies (equations 1, 2 3 and 4) corresponding to structural losses, are:

$$E_{uo} = \gamma \sum v_j \left[(z_j - z_l) + h_o \right] = 470880\ kWh/year$$

$$E_n = \gamma\ V_t\ H_n = 235440\ kWh/year\ ; \quad E_p = \gamma\ V_p\ H_p = 470880\ kWh/year \tag{7}$$

$$E_{si} = E_n + E_p = 706320\ kWh/year$$

$$\eta_{ai} = \frac{E_{uo}}{E_{si}} = 0.67; \qquad \theta_{ti} = 1 - \eta_{ai} = 0.33$$

Fig. 5. Radial branched irrigation network. First scenario.

The radial design of Figure 5 is common in irrigation networks (less flow per pipe, lower cost). The main energy problem is the shared energy source, that supplies a considerable surplus (not necessary) of pressure at the lower part of the network (40 m in the last row at zero elevation). To reduce θ_{ti} moving towards an eco-layout, the system needs to be decoupled, dividing it into sectors. The two new scenarios (2 and 3) are shown in Figure 6. In the second, with an identical network, the system is subdivided into two sectors, with two different pumps, one per sector. In the last scenario, all network rows are independent (each with its own pump, except for the last row that can be supplied by gravity).

The pump's characteristics in the second scenario are H_{p1} = 40 m; Q_{p1}=400 l/s and H_{p2} = 20 m; Q_{p2}=400 l/s, with the network being exactly the same (80 km). In the third case the network is divided into nine EMAs, supplied by eight different pumps (with H_{P1}= 40 m; H_{P2}= 35 m; H_{P3}= 30 m; H_{P4}= 25 m; H_{P5}= 20 m; H_{P6}= 15 m; H_{P7}= 10 m and H_{P8}= 5 m, seven equal flow rates Q_p=90 l/s, whereas the flow rate of the fifth pump is 80 l/s), because the supply to the final row does not require any pumping. The network is longer (92 km).

Fig. 6. Radial branched irrigation network. Scenarios 2 and 3

Reproducing the calculations made earlier (equation 7), the topographic energy percentage is 0.2 in scenario 2, and zero in scenario 3 (all the nodes are supplied with the required amount of energy). At this point we could believe that since the economy of scale is lost, the topographic energy reduction, and therefore the energy consumption, do not compensate for the extra costs of the installation. The following analysis deals with this question.

For the sake of clarity over accuracy, additional hypotheses are formulated:

- Pipe life is 50 years; pump life 15 years.
- Costs remain constant over time.
- To size the network and assess its cost, a unitary loss j has been set (m/km), irrelevant in the rest of the analysis (ideal system).
- All the pipes (PVC) share nominal working pressure (PN 6).
- The network cost is proportional to the square of the diameter, valid for PVC pipes, although any other formula (Swamee and Sharma, 2008) is acceptable.
- Installation cost can be included using a multiplying factor, F_i. In irrigation networks, 1.5 is a usual value.
- The friction factor f (needed to calculate pipe capital costs) is constant.
- The cost of pumps varies greatly and is therefore the most difficult element to assess. As a matter of fact, in identical conditions (performances, materials and manufacturer) a single pump can be more expensive than the two equivalent ones (same head, half flow each). In fact there are too many factors influencing the final cost of the pumps, the main one being installation. If, as in this case study, pumps share the pumping station house, capital and operating and maintenance (O&M) costs decrease dramatically. To calculate the cost, a power depending variation (Swamee and Sharma, 2008) is assumed although similar expressions (but with flow and head dependence being different) can be found in the literature (Walski et al., 1987).

- Motor and other components cost the same as the pump while O&M accounts for 15% of the total investment. This is a reasonable amount in water pumps with a shared power house (HI and Europump, 2001).
- The energy cost of the power term is included. The system only operates during off-peak hours (constant kWh value).

With all these hypotheses, the equations used for the economic analysis are:

a) Network capital costs

Unit cost, C_u (€/m), of a pipe:

$$C_u \cong k.\pi \cdot D \cdot e = k.\pi \cdot D.\frac{p \cdot D}{2 \cdot \sigma} = k' \cdot p \cdot D^2 \quad (8)$$

where *D* is the diameter (m), *e* the pipe thickness (m), *σ* the the material working stress (PVC), *p* the working pressure, and *k* a constant representing the cost of the material (€/m^3).

From the Darcy-Weisbach equation, the diameter depends on the flow rate, where j (unit head loss, 0.002 m/m) and f (friction factor 0.014) are constant. In SI units (the constant 0.0826 is not dimensionless), we arrive at:

$$D = \left(\frac{0.0826}{j} f q^2\right)^{1/5} \quad (9)$$

Combining (8) and (9), the result is:

$$C_u \cong K \cdot p \cdot q^{4/5} = K_p \cdot q^{4/5} \quad (10)$$

From the PVC pipe catalogue (PN = 6 bar), K_p is calculated (0.96), and the final network cost results:

$$I_T = F_i \sum l_i \cdot C_u(q_i) = 0.96 \cdot F_i \sum l_i \cdot q_i^{4/5} \quad (11)$$

If lengths and flow rates are known, the investment required for each scenario is known as well.

b) Pumping capital costs

Using an equation available in the literature (Swamee and Sharma, 2008) adjusted using real values, and considering the preceding hypotheses, we obtain:

$$C_p\ (€) = 1905.13 \cdot P^{0.72} \quad (12)$$

where P is the hydraulic power (kW). The annual cost is obtained from a pump life of 15 years.

c) Energy cost. Current values are assumed. In particular 0.08 €/kW (monthly power term) and 0.11 €/kWh (energy term).

Table 2, which synthesizes the results, proves that scenario 3 is the best in terms of energy and overall. On the other hand, as there are no operational losses (friction is only needed to size the pipe diameters) the analysis has focused on the ideal energy requirements, the subject in hand.

Table 2. Costs of the analyzed scenarios.

Finally, it is worth pointing out that:

- On quasi-flat land (in this case the slope is 0.5%), topographic energy also plays a relevant role. It is always important to manage it, not only in areas with steep gradients.
- Structural losses can be reduced by optimizing the topology. The dimensionless parameter θ_{ti} takes account of it.
- In this case study, an irrigation system with 1500 working hours/year, energy costs are smaller than in an urban network. Therefore, in similar conditions, the advantages of a topology approaching an eco-layout, should be higher.
- Due to the structural losses reduction, the contribution of natural energy, E_n/E_{si}, with more efficient layouts increases (0.33 in the first scenario; 0.5 in the third).
- Subdividing networks in EMAs from the beginning makes sense because the objectives of the DMAs and PMAs can be simultaneously met.
- And last, but not least, the economic analysis can be refined by applying real costs and including operational losses. But the procedure is identical and the result, will probably be the same. That is, in favor of the more energy efficient layout.

ECO-LAYOUT STRATEGIES VERSUS CURRENT WATER NETWORK MANAGEMENT ACTIONS . THE ANYTOWN EXAMPLE

As mentioned previously, the basic principle of an eco-layout is to minimize the difference between the delivered and the required energy, in practice a time variable value because networks are dynamic (with some exceptions, such as a programmed irrigation network, Figure 5). Demand and friction losses vary with time thus conditioning the supply pressure although the standard pressure is constant. This fact clearly shows that a RES is not, from an energy point of view, the most suitable. On the other hand, resilience (Todini, 2000), basically a surplus of energy (i.e. inefficiency), is only necessary in adverse situations (such as pipe breakage) but is not required on a permanent basis. Therefore, if the final goal is to reduce the energy requirements as far as possible, these traditional concepts must be revisited.

Tanks and eco-layout of networks

There are many reasons to install storage tanks. Among others, to improve the reliability of the supply, to guarantee the required pressure at points of consumption (working as a RES), to equalize the quasi-constant input flow (from a drinking water treatment plant) to the variable customers' demand in order to avoid over-sizing pipe systems and others (Walski, 2000). Solid design conditions have been established (Van Zyl et al., 2008) to determine the main parameters (elevation and volume). A lot of literature on the subject (Batchabani and Fuamba, 2012) is available.

These two main parameters have strong energy implications. On the one hand the elevation represents the supplied energy intensity while on the other, volume also has a significant impact on energy. Not so much in terms of work (kWh), but because of the final bill to be paid. A large storage capacity can avoid pumping at peak hours, and consequently the more expensive energy rate is avoided. But this is not for free because it is at the expense of bigger investments. Not only does it entail over-sizing the storage volume, but the main pipe diameter and pumping station must be generously dimensioned as well. In short, the cost of the energy is reduced (although not consumption) at the expense of increasing the investment and the peak-power requirement. On the other hand, the growing concern for water quality has done away with the idea that the bigger the storage tank the better (Walski, 2000).

As said previously, from an energy point of view, a tank cannot be as efficient as a variable (adaptable) source. It is important to underline that peak hours (which condition elevation) account for 10% of the daily operating time (two out of twenty-four hours). Consequently, a short period of time is used to decide the height of the tank, and consequently, throughout the rest of the day there is a surplus of energy which must be removed via PRV or recovered using PATs, in order to avoid excessive pressures.

Moreover, since the average life of a tank is 75 to 100 years (SSWD, 2011), deciding on its location (which can come into conflict due to aesthetics), is a long-term decision. More often than not, in order to avoid conflicts and the risk entailed in the passing of time (growth of the city), the elevation is usually over-estimated, locating the tank on the highest hill around the city (as represented in the Figure 2), thus energy-wise mortgaging the system. These criteria, logical some decades ago, need to be reviewed. There can be, indeed, a certain volume of back-up water (to guarantee supply and to use in case of fire) in the storage tank. But it must be placed at the exit of the potable water treatment plant (same elevation), and then energy must be injected by means of a variable source (Figure 4). In other words, the capacity is given by the base storage tank (with less energy consumption) while the pumping system provides the necessary additional energy, as this varies with time.

Technology permits parallel pumping groups and motors fitted with VSD that can continue inject the exact amount of required energy into the system regardless of demand. It is also important to have generators, with several days' autonomy, to supply power in the event of an electricity network failure. On the other hand, since pumps have an average life ranging between 15 and 20 years (SV, 2009), it will be easier to adapt them to changing requirements over time. Finally, strictly in terms of energy, it must be stated that the financial savings of avoiding peak hours energy, does not set off the advantages of direct injection (Gomez et al., 2015).

Resilience versus rigid and variable energy sources

Since the concept of resilience spread to water supply, proposing an index to quantify it (Todini, 2000), many other articles have emphasized their interest, and some have even proposed alternatives to this pioneer index (Jeong et al., 2017). It is, as stated earlier, a measure of the surplus energy in the network, necessary to compensate for falls in pressure in the event of a critical scenario. But if the source is rigid, that surplus, only necessary occasionally, is permanent, and that means inefficiency.

It is worth remembering the importance of adequate pressure management (PM), bringing it as close as possible to the pressure set by the standards (GIZ, 2011). Hence, any PM entails a loss of resilience. Therefore, it seems more logical to design the system to fulfil the steady standard conditions with a VES, a source of energy able to cater for any critical events (e.g. increasing the pump speed). Obviously the required response for each incident must be previously foreseen and characterized.

DMA, PMA and eco-layouts

While tanks and the concept of steady resilience appear to be contradictory to the objective of minimizing the energy requirements, sectorizing the network in DMA and/or PMA, are actions that are fully in tune with it. Moreover, an EMA has identical objectives to a PMA and, at the same time, can work as a DMA. Additional sectorization is only advisable in large EMAs.

To summarize this, designing eco-layouts implies a reduction of the range of elevations served by a pressure zone. Instead of covering a range of elevation of say, 40 m, they must cover smaller ranges, adapted to each particular case. This strategy has negative (higher investments are needed) and positive sides (energy and emissions savings). Therefore a cost-benefit analysis is, in the end, required to make a final decision. In any case, it is worth remembering that in most of the pumps Life Cycle Cost analyses, energy costs are much more higher than capital costs (HI and Europump, 2001). And we cannot forget the last advantage mentioned earlier, the inherent benefits associated with correct PM (GIZ, 2011).

The Anytown network subdivided in EMAs

The Anytown system (Walski et al., 1987) is a well-known case study, a network (Figure 7) that is suitable to illustrate the concepts established here since the consumption nodes are on four different horizontal platforms (20 ft, 50 ft, 80 ft and 120 ft), with the water source located at the lower node (10 ft). A number of compensation tanks (two or three depending on the analyst, although this is irrelevant for the question in hand) are at 215 ft. The working pressure is 40 psi (86.25 ft), a value approaching the difference between the tank elevation (215 ft) and the highest node level (120 ft) plus the standard pressure (86.25 ft), an appropriate value to fill the tanks during off-peak hours. With this layout, the topographic energy is notable. As will be seen by comparing scenarios, the reason for this is the energy rigidity of the compensation tanks.

The system is assumed to be ideal, although this hypothesis, owing to the presence of compensation tanks, is not logical. Indeed, in real operation, these tanks are filled during off-peak hours and are emptied during peak hours. Nevertheless, in an ideal case we should suppose the opposite. With a pumping height equal to the difference between the highest and lowest heights (215 - 10 = 205 ft) and a flow rate equal to peak demand, the tanks (at a constant height, regardless of whether the flow is incoming or outgoing) will be filled during off peak hours, acting as a demand node. Once full, the pumps stop and the tanks supply the demand, working as a source. When brought down to their normal low level, pumping starts again. That would be the cycle. The compensation tanks, meaningless in an ideal scenario, have been kept to exactly replicate the initial layout, even their elevation in ft (in the rest of the paper, the SI system is used). Operation has a common denominator: the energy source (tank or pump) always supplying

215 ft, a simplification that shows the dependence on the topographic energy of the system layout. In the real system the conditions change every hour, and the energy balance is more complex since in short periods the compensation tanks intervene in the audit (Cabrera et al., 2010), but the concepts are identical.

Fig. 7. The Anytown network (Walski et al., 1987).

The other two scenarios considered, more logical with current hypotheses, Figure 8, are:

a) There are no compensation tanks (Figure 8.a).

b) Four independent pumps, one for each consumption plane (four EMAs, Figure 8.b).

In the second scenario (Figure 8.a) pressure is equalized to the requirements of the highest level (pumping height = 120 + 86.24 -10 = 196.24 ft). But since the reduction in height of pumping is rather discrete (less than 5%), the improvement is not relevant. Nevertheless, sectorizing the system in four EMAs (Figure 8.b), in line with that discussed previously (Figure 6, scenario c), and supplying the required energy to each node (heights equal to 196.24 ft, 156.24 ft, 126.24 ft and 96.24 ft), the topographic energy is zero and the achieved savings are considerable. Finally, Figure 9 compares the basic hydraulic functioning of the three scenarios, which permits better understanding the savings and the role of the standard pressure $h_{o.}$

Fig. 8.a. Anytown, direct pumping. **Fig. 8.b.** Anytown, decoupled, direct pumping.

Fig. 9. Hydraulic diagrams (a.- scenario 1; b.- scenario 2; c.- scenario 3)

Table 3 shows the daily energy balance. The energy cost for the third scenario is 30% lower than the initial one, with important savings. Around US$100,000/ year, assuming a cost of 0.12 $/kWh, respecting the original data (Walski et al., 1987).

Table 3. Comparative energy balance of the three analyzed scenarios

In short, minimizing the required energy entails sectorizing the network from its conception, because doing it later is difficult unless structural changes, similar to those considered, are implemented in the layout. Finally, to avoid connectivity losses (necessary to increase the network's reliability) in the third scenario additional pipes have been included (Figure 8.b, discontinuous lines) to enhance the reliability of the system.

Finally, and although there are networks with different connectivity, to complete this analysis a cost study has been performed. Because it is the most cost-effective solution proposed, we have compared Gessler's network (Walski et al., 1987) with the eco-layout of Anytown (figure 8.b). The network has been sized fulfilling identical service conditions than those stated in the original competition. With identical data (same C-factor and equal unitary pipe costs), Gessler's network is around 1% cheaper than the eco-layout of Anytown (including the additional pipes to improve connectivity). Therefore the whole proposed system will require a lower investment because additional pumping station costs should be widely compensated by civil works savings (tanks are not needed) and, furthermore, with 30% energy savings .

PROTOCOL TO MINIMIZE THE ENERGY REQUIREMENTS IN WATER NETWORKS. FINAL REMARKS

The ultimate goal of any water network is, no matter its final use, to deliver adequate quantities of water to the different points of use at an adequate pressure established by the regulatory standards, currently 20 – 25 m (Ghorbanian et al., 2016). For irrigation use, the pressure is set by the devices needs (drippers or sprinklers). And the requirements must be met with the minimum amount of water and energy, i.e., avoiding losses. In particular, this paper is devoted to minimizing the structural energy losses.

Figure 10 presents the protocol to reduce both kinds of energy losses, structural and operational. The upper rectangle of the left side column corresponds to the analyzed eco-layout process. A strategy that, we know from our own experience, can be unpopular because it is not easy to convince users with 60 m of service pressure that, in order to improve the efficiency, this value must be drastically reduced to the standard value (say 20 m). What is evident for engineers is not for consumers. In any case, this should be a matter of future discussion between all players (customers, managers and operators of water systems and regulators). The lower rectangle of Figure 10 summarizes the well-known PM strategy implemented with PATs and PRVs. The whole left column shows the three Rs (reduce, recover or remove) actions described earlier.

The right side column is the protocol devoted to minimize the operational losses. A process that summarizes the term eco-management, synthesis of the Eco-management and Audit Scheme process, EMAS (EC, 2011). In fact, the two first actions are the network audits (water and energy). Both columns are coupled because fitting PATs and PRVs reduces leaks, modifying the water balance and therefore the energy balance as well. This diagram is an improved version of a former one (Cabrera et al., 2017), devoted more specifically to the operational losses, ignored in this paper but widely reported in the technical literature.

On the contrary structural losses have been disregarded until now. Perhaps because reducing them involves complex, long-term actions that may even be seen as Utopian and, therefore only applicable to new systems. However, it is important to underline that these actions can be implemented gradually in operating systems (Cabrera et al., 2014). This is a similar case to energy improvement actions in existing buildings. Although they are long-term assets (over 50 years), being responsible for about one-third of the world's energy consumption, they are key objectives in developed countries. Energy efficiency programs (EEFIG, 2015) are tailored to that purpose. In the end, all the systems are dynamic, with their components having different life-expectancies. And for any strategic asset management plan knowing the way towards a more sustainable behavior of the asset is crucial.

To summarize, there are two ways to reduce structural losses. To equalize the delivered pressure to the required one as much as possible, and to subdivide the system in EMAs. Concerning each strategy important remarks apply. With regards to the first one:

- A new debate arises: in urban water networks, what should the minimum pressure requirement be? Up to now, literature provides little information on this. Although Ghorbanian et al., 2016 have discussed current pressure standards in some relevant countries, they do not actually answer that question. This is a subject that should be addressed at local level, where the answer could be merging hydraulics, considering the characteristics of cities (in some places, achieving lower pressure requires localized pumping in comercial and residential properties) and the expectations of customers.
- High water pressures have pros and cons. From the point of view of utility, clear advantages are higher resilience, greater water consumption and better pathogen intrusion prevention. On the negative side we find a higher level of leaks, higher stress on pipes (that means shorter pipe life) and, for sure, higher energy consumption. Therefore, in this era of climate change, the debate continues.
- The analysis must include an additional factor. When water pressure is near to minimum standard, when emergencies arise (e.g. fire, burst pipes, etc.) an additional source of energy is required.
- In less demanding uses (e.g., irrigation) the preceding debate is not so relevant. Pressure should be as close as possible to requirements.

With regards to subdividing the system in EMAs, it is important to emphasize that:

- The eco-layout is an approach which is dependent on the area and has a rational and economic limit. It is obvious that the pressure in every house cannot be supplied at exactly the required minimum pressure. In flat areas or where sloping land is uniform, to subdivide the network in EMAs will be much easier than in undulating areas.
- In operating systems, implementing this strategy is much more complex than in new ones, and will always require a cost benefit analysis, similar to those preceding a DMA division. In any case creating an EMA will always be more expensive (requires extra

pipes and pumps) but more economic benefits will be obtained (the EMA can work as well as a DMA). In conclusion, the shift from Figure 2 to 3 is not for free. Taking into account operational implications, it must be traded off and should also include a life cycle analysis.

In the end, having properly established the eco-layout fundamentals, in real systems the final decision can be taken from the comparison of the two scenarios (the actual versus the new), obviously including operational losses. This analysis will foster the mutation towards more efficient topologies. In any case, as has been underlined, we are speaking about a long, complex process.

Fig. 10. Protocol to reduce the energy requirements in water networks

CONCLUSION

In order to minimize energy consumption in a pressurized water network, the basic principle is fairly simple: as far as possible, deliver the required pressure at any time. More is a waste, and less fails to meet the quality standards. A principle easy to spell out, but far more complex to implement, particularly in areas with irregular topographic profiles. Not so much in areas with uniform slopes no matter the value, because even with small steps the structural energy losses can amount to a significant figure. Topographic energy is quantified in parameter θ_{ti}, the complementary value of ideal performance η_{ai}. Minimizing θ_{ti} (equivalent to maximizing η_{ai}) is the ultimate goal of the eco-layout achievable by reducing the structural energy losses. This is achieved through flexible energy sources and dividing the network into EMAs.

The systems discussed, based on real cases (except for the Anytown network), prove the great energy saving that can be achieved with adequate eco-layouts. And although, for the sake of clarity, the analyzed cases have been considered ideal, in real situations the differences would be even greater because in these energy balances, any inefficiencies (friction, leaks, pumping losses or any others) increase the figures and consequently the new comparison (assuming similar levels of efficiency in the compared scenarios) would be even more beneficial. And further still if the analysis covers the entire life cycle. This is worth bearing in mind in new systems and existing systems that are to be refurbished in the future.

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Table 1. Energy balance of the ideal decoupled system (Figure 3)

Subsystem 1	Subsystem 2	Whole system (decoupled)
$E_{uo,1} = \gamma[(20[(70-0)+20])]\Delta t =$ $= \gamma 1.8\Delta t\ J$	$E_{uo,2} = \gamma[(80[(20-0)+20])]\Delta t =$ $= \gamma 3.2\Delta t\ J$	$E_{uo,g} = E_{uo1} + E_{uo2} =$ $= \gamma 5\Delta t\ J = E_{uo}$
$E_{ti,1} = \gamma \sum v_j \left((z_h + h_{o,h}) - (z_j + h_{o,j}) \right) =$ $= \gamma[(20(100-90)]\Delta t = \gamma 0.2\Delta t\ J$	$E_{ti,2} = \gamma \sum v_j \left((z_h + h_{o,h}) - (z_j + h_{o,j}) \right) =$ $= \gamma[(20(40-40)]\Delta t = 0\ J$	$E_{ti,g} = E_{ti1} + E_{ti2}$ $= \gamma 200\Delta t\ J < E_{ti}$
$E_{si,1} = \gamma V H_{hi1} = E_{uo1} + E_{ti1} =$ $= \gamma\ 20\ 100\Delta t = \gamma 2\Delta t\ J$	$E_{si,2} = \gamma V H_{hi2} = E_{uo2} + E_{ti2} =$ $= \gamma\ 80\ 40\Delta t = \gamma 3.2\Delta t$ J	$E_{si,g} = E_{si1} + E_{si2} =$ $= \gamma 2\Delta t + \gamma 3.2\Delta t$ $= \gamma 5.2\Delta t < E_{si}$

Table 2. Costs of the analyzed scenarios.

	E_{uo}	E_n	E_p	E_{si}	η_{ai}	θ_{ti}	L_t	Investment in pipes	Investment in pumping	Energy cost	Total cost
	kWh/year	kWh/year	kWh/year	kWh/year			km	€/year	€/year	€/year	€/year
Sc. 1	156960	78480	156960	235440	0.67	0.33	80	45418	18654	60963	125035
Sc. 2	156960	78480	117720	196200	0.80	0.20	80	45418	18148	45722	109288
Sc. 3	156960	78480	78480	156960	1	0	92	47925	19487	30482	97894

Table 3. Comparative energy balance of the three analyzed scenarios

	Scenario 1	Scenario 2	Scenario 3
E_{uo} (kWh/day)	6855	6826	6826
E_{ti} (kWh/day)	2247	2134	0
E_{si} (kWh/day)	9102	8960	6826
η_{ai}	0.75	0.76	1.00
θ_{ti}	0.25	0.24	0.00
Cost ($/day)	1092	1075	819

Figure 1

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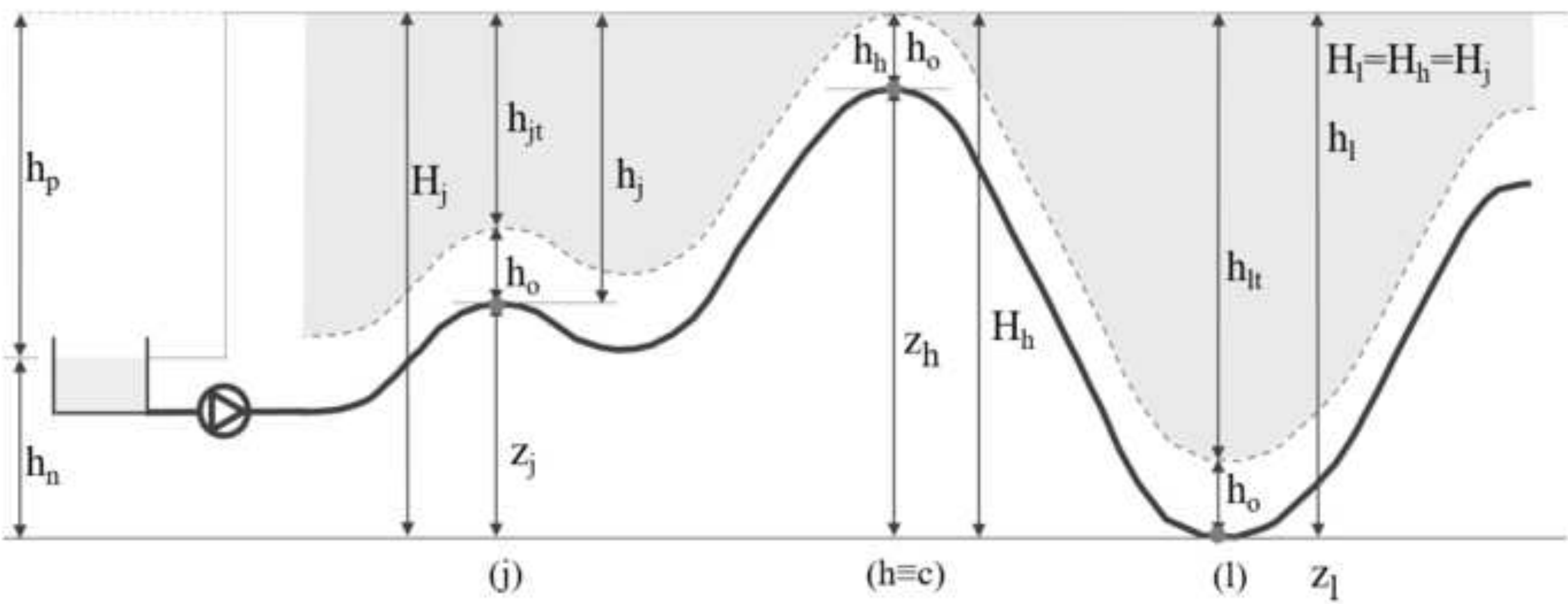

Figure 2

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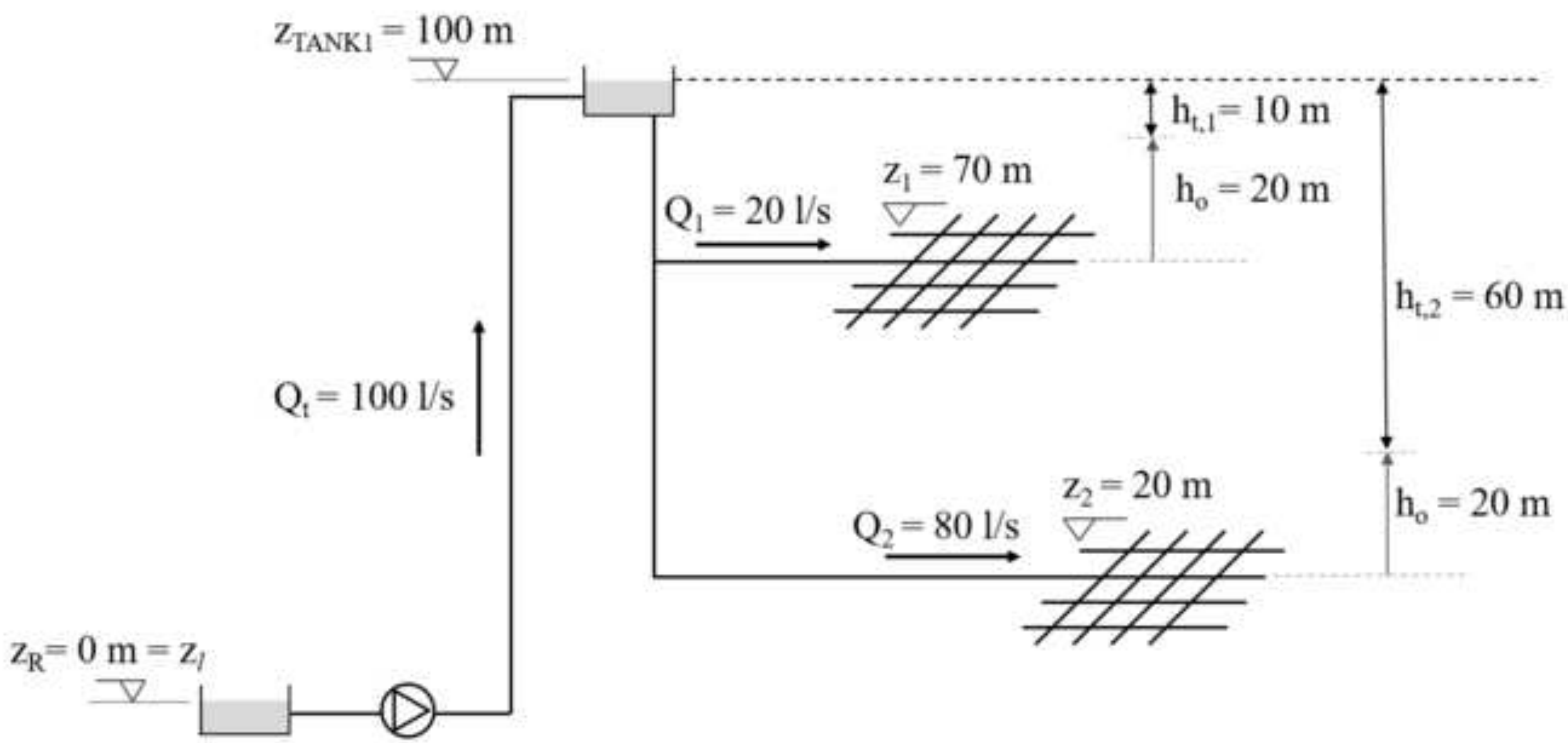

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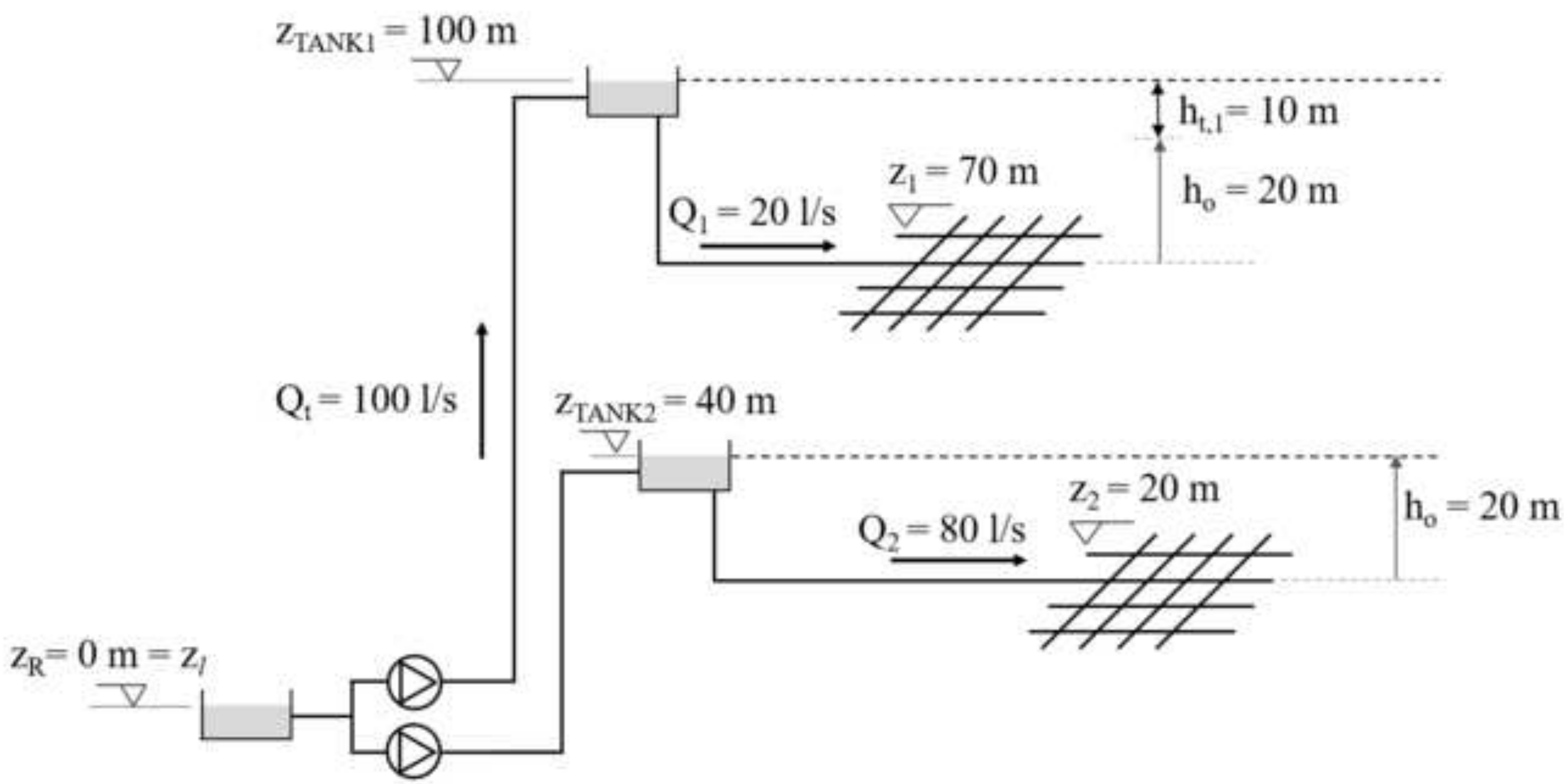

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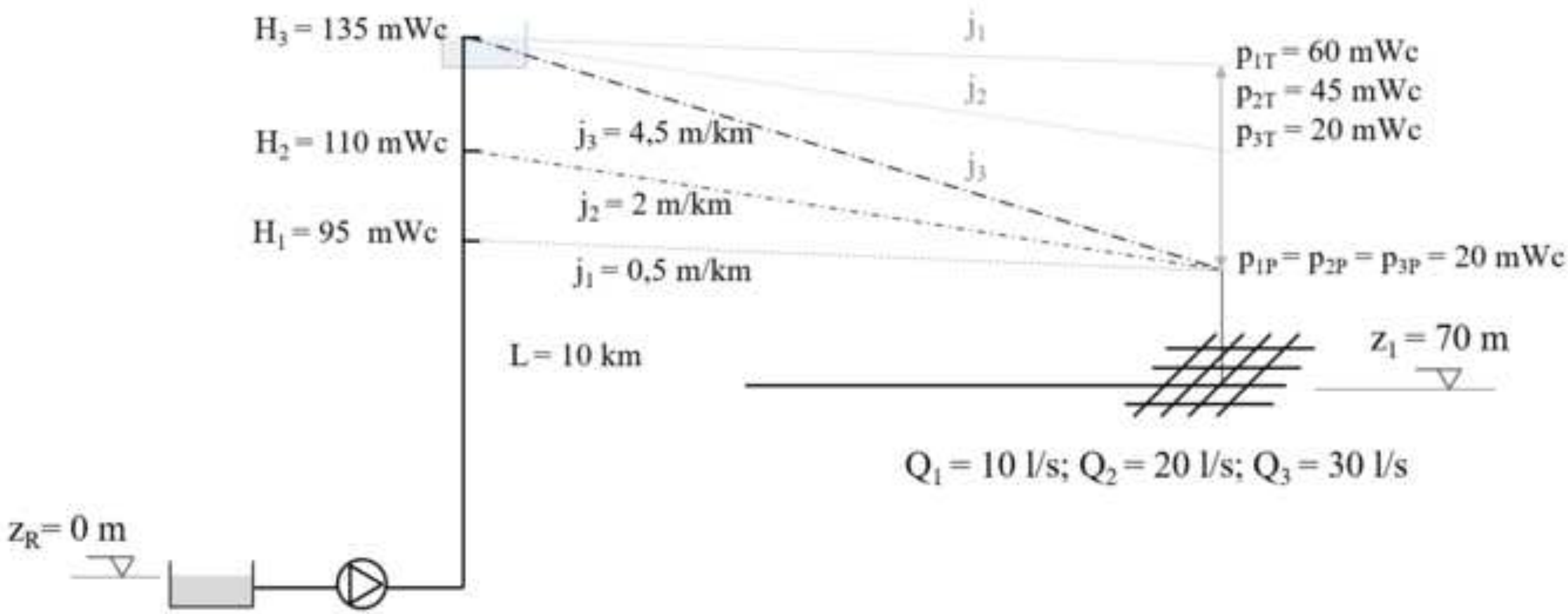

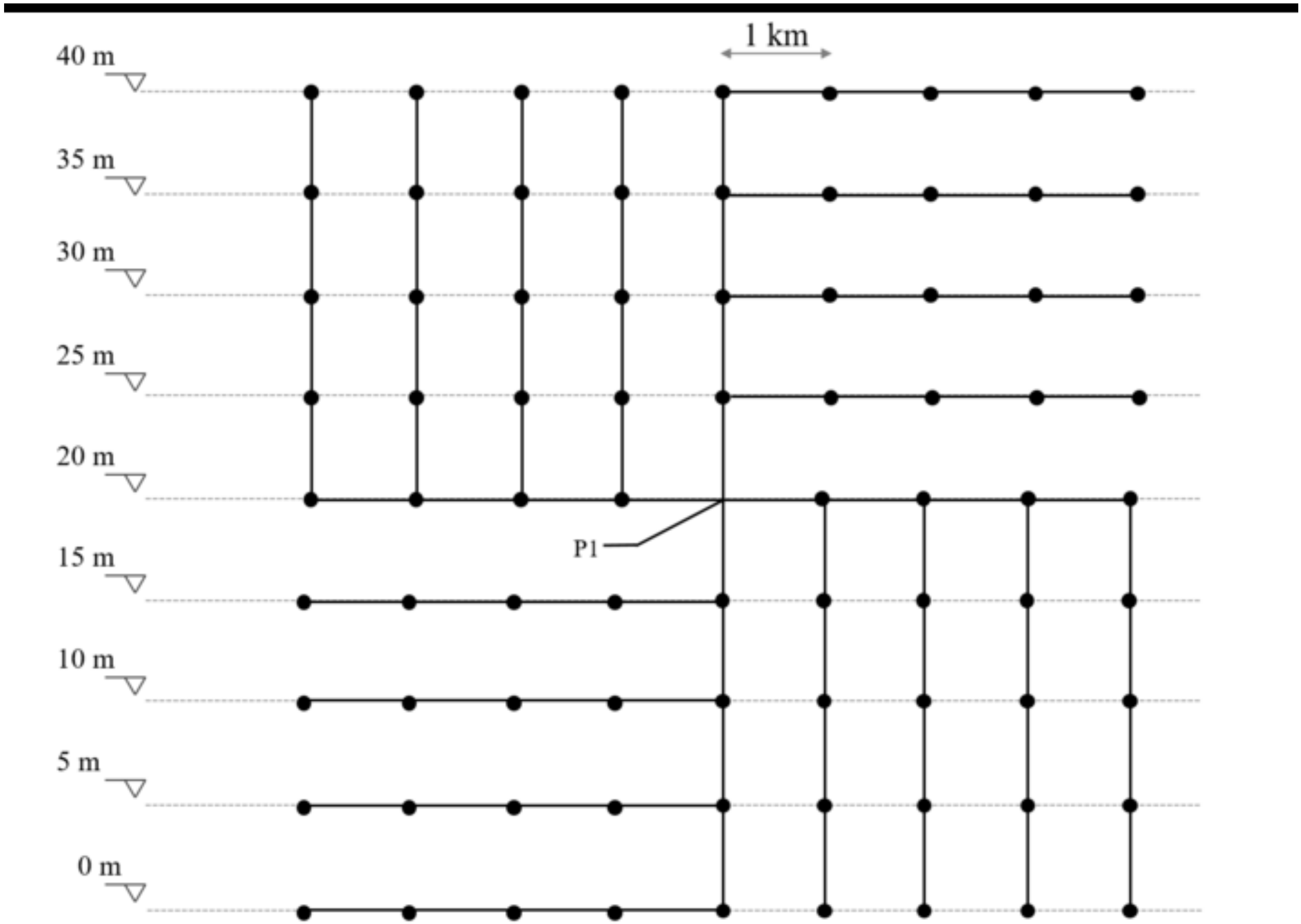
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5 m
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Figure 6

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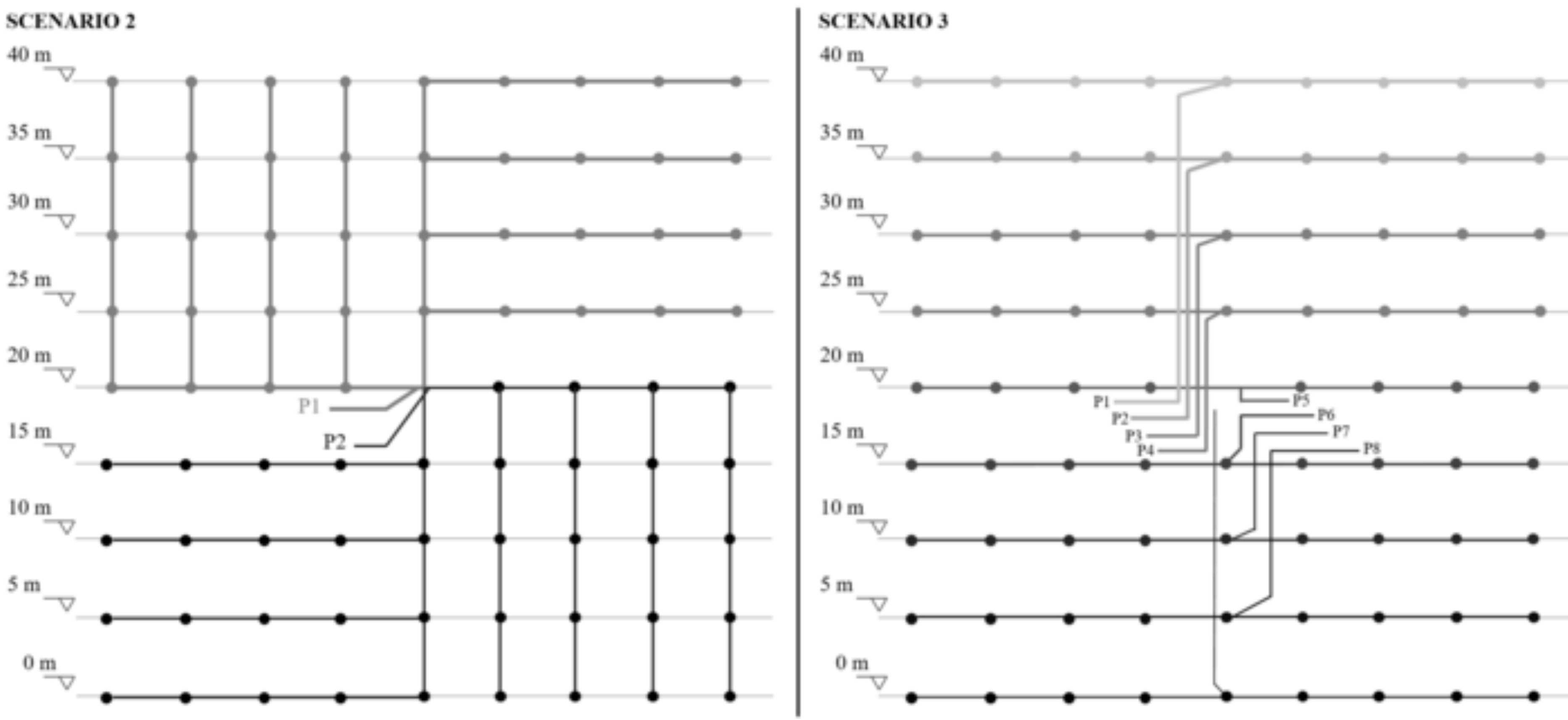

Figure 7

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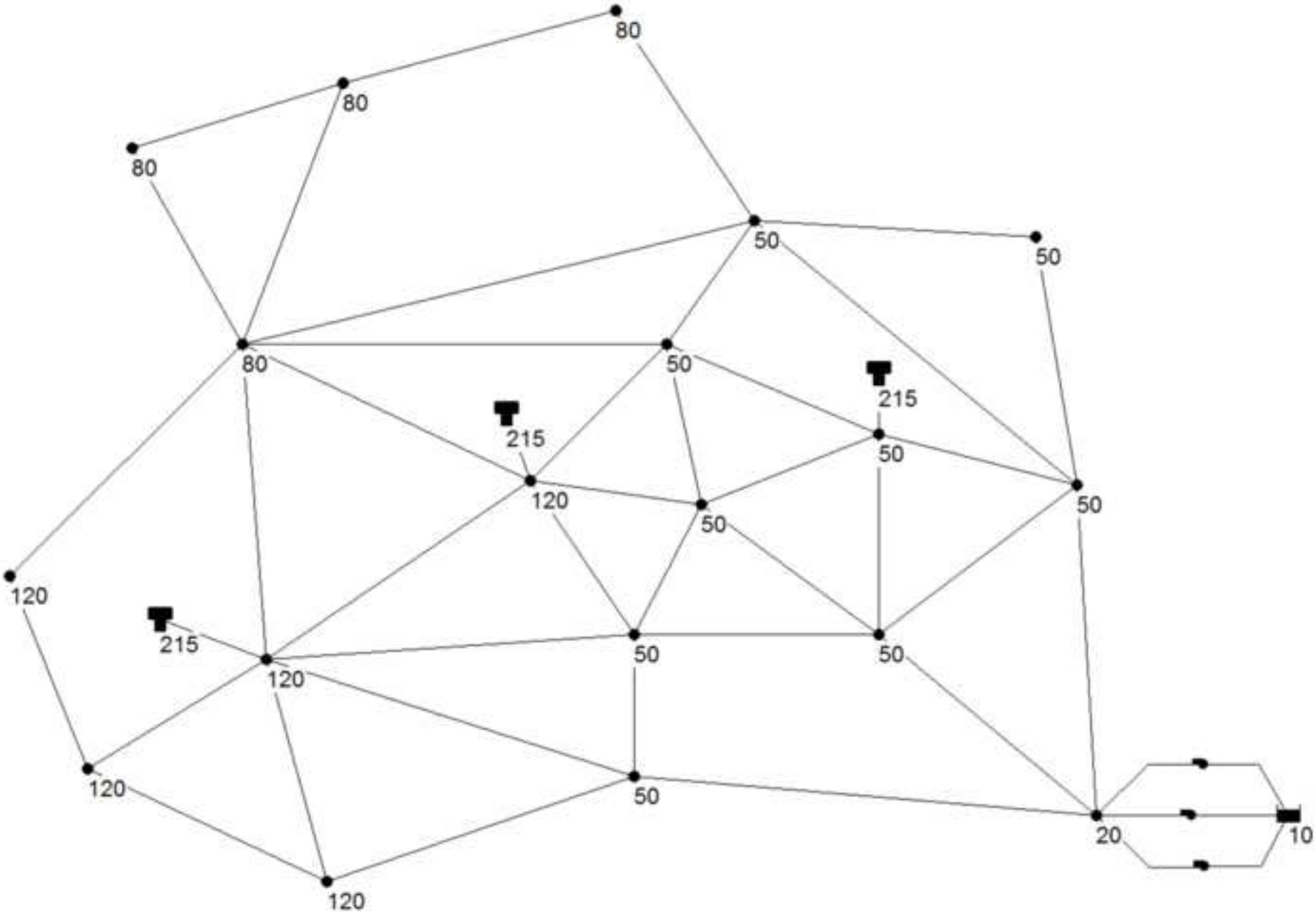
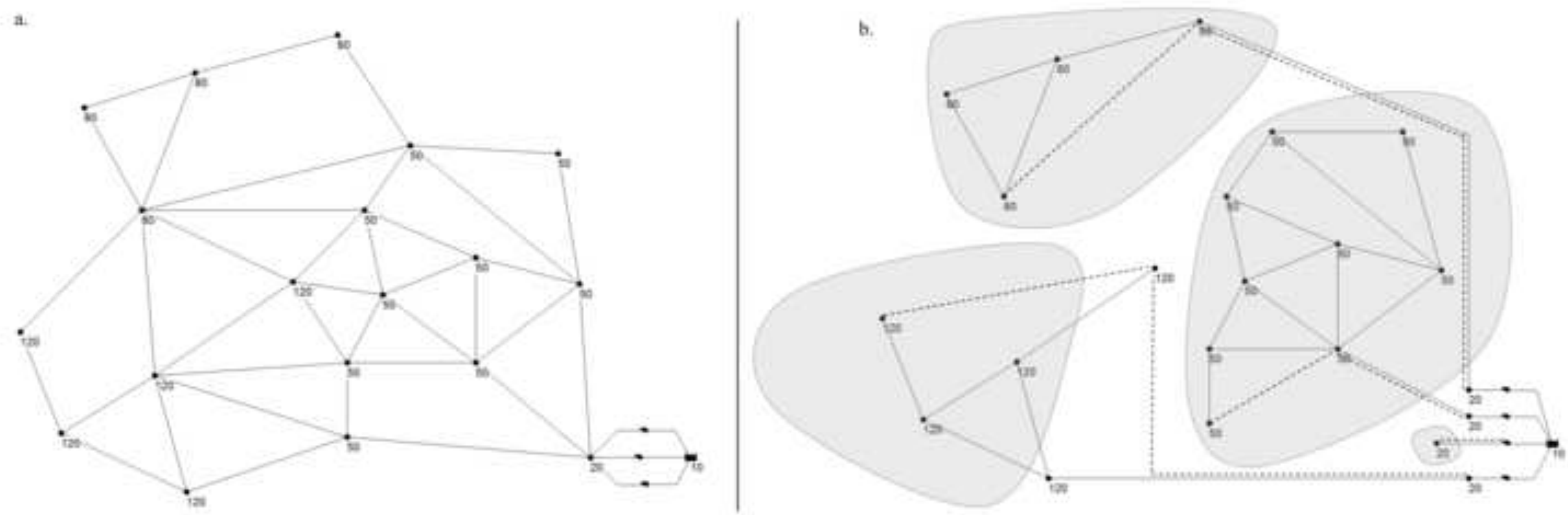


Figure 8



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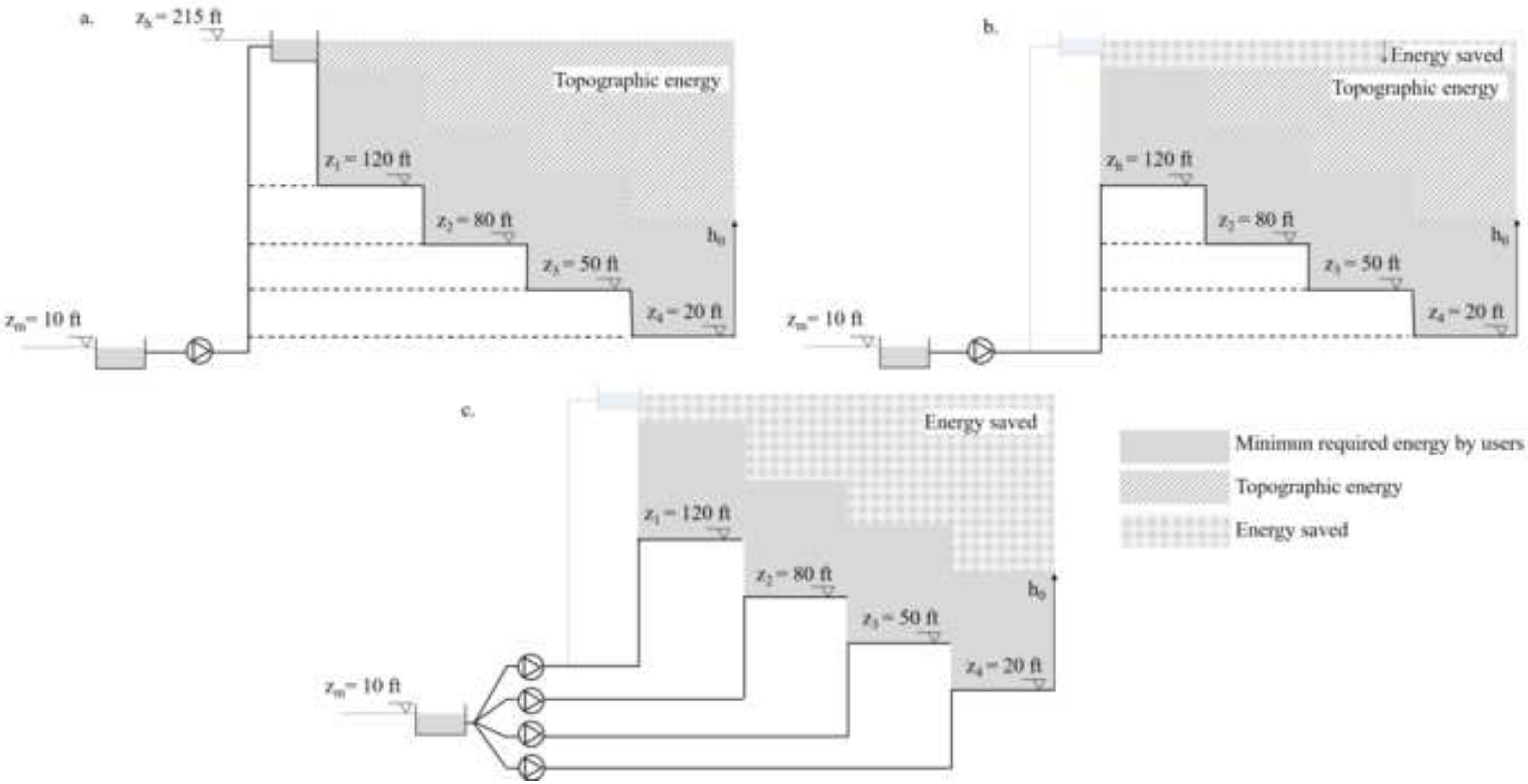
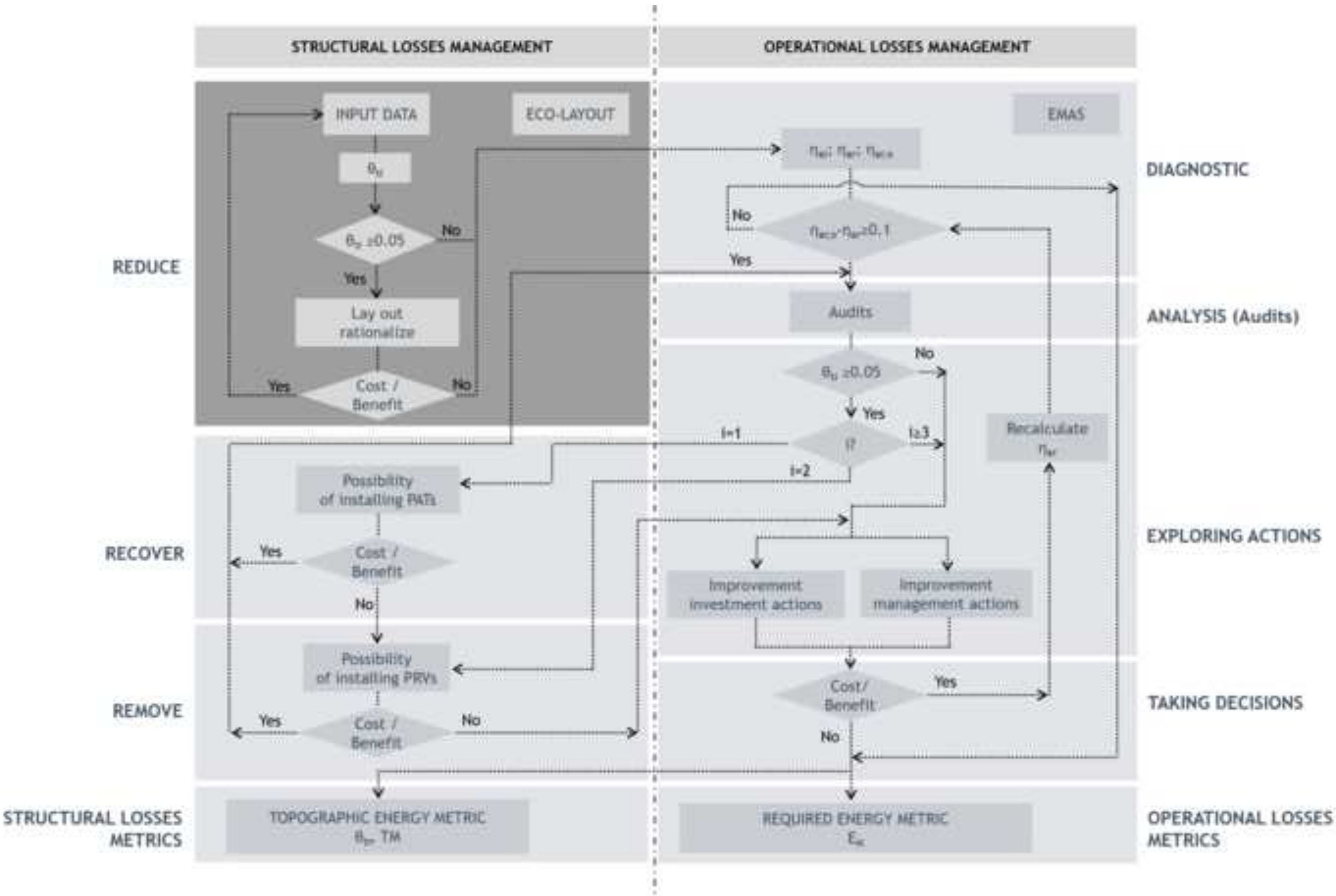


Figure 10


STRUCTURAL LOSSES MANAGEMENT
OPERATIONAL LOSSES MANAGEMENT
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ECO-LAYOUT
EMAS
REDUCE
DIAGNOSTIC
No
Yes
Lay out rationalize
Cost / Benefit
ANALYSIS (Audits)
Audits
i=1
i=2
i≥3
Recalculate
Possibility of installing PATs
RECOVER
EXPLORING ACTIONS
Improvement investment actions
Improvement management actions
Possibility of installing PRVs
REMOVE
TAKING DECISIONS
STRUCTURAL LOSSES METRICS
TOPOGRAPHIC ENERGY METRIC
REQUIRED ENERGY METRIC
OPERATIONAL LOSSES METRICS

Figure Captions

Fig. 1. Topographic energy concept in an ideal system (from Cabrera et al., 2014)

Fig. 2. Ideal system simultaneously supplying two zones located at different levels

Fig. 3. Ideal decoupled system (two subsystems)

Fig. 4. Supply with VES, equaling the required pressure and the supplied pressure

Fig. 5. Radial branched irrigation network. First scenario

Fig. 6. Radial branched irrigation network. Scenarios 2 and 3

Fig. 7. The Anytown network (Walski et al., 1987)

Fig. 8.a. Anytown, direct pumping. **Fig. 8.b.** Anytown, decoupled, direct pumping

Fig. 9. Hydraulic diagrams (a.- scenario 1; b.- scenario 2; c.- scenario 3)

Fig. 10. Protocol to reduce the energy requirements in water networks

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Comments to the Editor:

The extent of the paper has been significantly shortened. The main changes we have made are:

- Section "ACCUMULATED DISTRIBUTION OF TOPOGRAPHIC ENERGY" has been completely removed (approximately 3 pages). The concept presented here is of enormous interest, but collateral to the focus of the paper. For that reason, we will include it in a future paper (not as dense as this one).

- 5 figures have been removed (from Figure 7 to Figure 10 and Figure 14).
- The less significant or duplicated references have also been removed (11 in total).

The final result is a reduction from 46 to 36-37 pages in line with the editor's suggestion.

All comments suggested by Reviewer #2 have been appropriately addressed (see specific responses to Reviewer #2)

Comments to the reviewer #2

REVIWER#2	AUTHORS
I have read the new paper with interest and found it improved in content and explanation. It manages its topic much better with improved focus and development. Thus, I am comfortable now to recommend acceptance and just have a few suggestions (minor modifications) to make as the paper goes to publication.	
The abstract is better but still says too little about the actual explorations the paper contains. More specifically, in line 8, the term "objective" is used, but I think "topic" is a better work for this.	We agree with the reviewer, the term "objective" was replaced by "topic".

Water distribution systems inevitably are planned, designed and implemented with many objectives in mind. The aspects of, say, energy delivery have to be balanced with historical investments, budgets, costs, reliability, flexibility, and numerous other constraints. The problem with focusing on one of these aspects (as the paper so obviously does) is it tends to push other objectives into the constraints and then pushes up against the constraint boundaries. This paper does this with pressure constraints, in that the minimum pressure criteria almost become also the maximum pressure criteria. I understand and appreciate how and why this has happened in the text, but I think the multi-objective nature should be acknowledged sooner in the paper. Only near the end does the paper admit, for example, that consumers may well like pressures well above the minimum pressure standard, and that a move toward the minimum might be seen as unpopular. The point here is that "consumer satisfaction" is also an objective.	Of course, customer satisfaction is an objective for managers, and the pressure supplied to customers is one of the variables to be taken into account. The paper is not intended to discuss whether the pressure values supplied are enough or not, this question has to be addressed by the regulation itself. In our paper, this pressure is a boundary condition (set by the water utility/standards, etc (as indicated in lines 29-30, 55-56, 89, etc.
We have seen Fig. 1 in previous versions but this figure strikes me now that I am more familiar with the paper as rather extreme. In particular, the delivery pressure (ho) is drawn as though it is a small fraction of the topographic variation. This would only be true in rare cases. Would not a more realistically scaled plot actually make the point more clearly?	At this point, we consider that including a comment (Figure not to scale) directly in the figure caption may be a good solution for better understanding.
A repeated, though trivial, irritation is that the variables following an equation are introduce with a "Where" (capital W), as though this was a new sentence. Another trivial suggestion for the authors to scan their paper to see how many uses of the term "very" actual contribute any value. This word in English has little power as an intensifier. Most (all?) of these can be nicely removed I think.	Following your suggestion "Where" has been replaced by "where" and the term "very" has been removed.
Line 69 and 70 implies good management can reduce operational losses to zero in ideal systems. This sentence is either annoying (I have operational losses thus I am not a good manager) or meaningless (since no system is ideal). Why not just say that operational losses are often high in practice	We agree with the reviewer. The new sentence is: "These losses are often high in practice and thus need careful attention by management (in an ideal system these losses should be zero)".

and thus need careful attention by management, but that these losses are not the subject of the current paper? It is not practical, for example, to reduce friction to even near zero without compromising water quality or greatly increasing capital costs. No pump is 100% efficient.	
Line 131 uses the term "optimal" too casually. This is one option only and the fact has not been established. Why not say something like, "It is likely better in many contexts to reduce topographic through the layout of the system itself"?	Yes, this term has been replaced by the reviewer's suggestion.
For this whole section (starting on Line 125) might this not be delayed until later in the paper, rather than interrupting the flow of the argument relating exclusively to the main topic of the paper (topographic energy)?	We understand the reviewer's comment, but we cannot move the section forward to the introduction of the concept behind it, neither after the case study.
There are still quite a few places where the sentence structure is rather awkward and clunky. I think an editor or final type setting can perhaps help with this.	We have removed an entire section (which we consider more collateral) and this probably makes the paper easier to understand.