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Water Resources Management

TOPOGRAPHIC ENERGY MANAGEMENT IN WATER DISTRIBUTION SYSTEMS

--Manuscript Draft--

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Abstract:	A significant amount of energy is required to operate pressurised water distribution systems, and therefore, improving their efficiency is crucial. Traditionally, more emphasis has been placed on operational losses (pumping inefficiencies, excess leakage or friction in pipes) than on structural (or topographic) losses, which arise because of the irregular (unchangeable) terrain on which the system is located and the network's layout. Hence, modifying the network to adopt an ecologically friendly layout is the only way to reduce structural losses. With the aim of improving the management of water distribution systems and optimising their energy use, this work audits and classifies water networks' structural losses (derived from topographic energy), which constitutes the main novelty of this paper. Energy can be recovered with PATs (pumps as turbines) or removed through PRVs (pressure reducing valves). The proposed hydraulic analysis clarifies how that energy is used and identifies the most suitable strategy for improving efficiency as locating the most suitable place to install PRVs or PATs. Two examples are discussed to illustrate the relevance of this analysis.

EDITOR	
Comment	Action
The paper is indeed interesting, but it needs further scientific and language editing. The authors are advised to consult a native English speaker before submitting the revised manuscript to the journal. We at the journal think that loose writing or texts with grammar and syntax mistakes cannot be processed further for publication. If the authors do not have access to any editing service, they can always ask for assistance the Editing service of Springer for editing at a low cost.	The text has been revised by an English editorial service (Springer Nature Author Services) in order to correct English grammar errors and expressions. Please find attached the Editing Certificate.
ASSOCIATE EDITOR	
The paper has the potential to be published in WARM after careful revision. In the revised version of the paper, the authors are asked to clearly state which is the novelty of the paper for which the paper deserves publication.	The paper has been carefully reviewed and the new version considers all the points and concerns of the reviewers. We recognize that they have done an excellent job and, because of that, we have included our gratitude at the end of the paper. The novelties of the paper have been underlined in the most relevant sections of the paper (abstract and conclusions).
The authors are also advised to follow strictly the Guide for Authors and the section «Statements e.t.c. ». It should be clear that papers of a size which exceeds 8000 words (including text, references, figs and tables) cannot be processed further for publication. Each fig/table is counted for 300 words. Please check that no more than 10 – 15 % of the references are from the same journal and no more than three references are from the same author	We have done an important effort for reducing significantly the extension of the paper: the entire section 4 has been deleted, together with 3 tables and 3 figures. In addition, the main text has been revised in order to reduce as much unnecessary text as possible. As far as the self-citations concerns, they have been cut in half (from six to three). The references from a same journal (Water Resources Planning and Management) have been reduced from 11 to 4. Citations from this journal have been also reduced to 4. It is complicated to further reduce these numbers because most of our previous work has been published in these Journals. As a consequence, the references have been reduced by a third (from 31 to 19).
Finally, avoid parts of text, which have been published previously in other papers of yours. Our i-thenticate system can check for this overlapping percentage. Generally, for papers submitted to the journal, this percentage cannot exceed the 20% limit.	The contents of this paper are new. As usual, new developments are based in previous works. They have been briefly commented in the text as some concepts are needed to understand the paper Nevertheless, these descriptions have been dramatically reduced in this new version.
REVIEWER 1	
1 INTRODUCTION	
The paper shows the energy analysis in water distribution networks. This is an interesting research and the paper is well organized.	Thank you very much.
The case studies presented are very simple and for more complex networks, especially with multiple sources, the methodology is not clear.	We agree with the reviewer; the examples are very simple in order to clearly illustrate this new methodology, as the purpose of this work is to present its fundamentals. A more complex system can be performed following the explanation of section 2, including the new equation 4, that clarifies the calculation with multiple sources.
The conclusion does not highlight the advantages of this energy analysis when compared with other approaches for design and management of networks	Traditional approaches look for minimize pressures and leaks with mathematical tools (optimization problems). The focus of this new approach is on the structural losses. The nodal topography energy audit is calculated from the networks' behavior (hydraulic approach). These differences have been underlined in the paper and specifically added in the last paragraph of the conclusions section.
The authors should explain in the introduction section what is the novelty of the paper, since the methodology presented in this paper is defined and applied in Cabrera et al (2014) and Cabrera et al (2019).	The novelty of this paper is the nodal topographic energy audit and management. What has been defined in previous papers are two basic concepts: topographic energy (Cabrera et al., 2014) and the structural energy losses (Cabrera et al., 2019). The objective of this work is how to perform a nodal topographic energy audit, how to manage this energy and therefore, how it can be minimized. This point has been clarified in the paper, in particular in the abstract, introduction and conclusions.
Page 3, line 27 – the major problem in intermittent systems is the occurrence of water hammer. This is a different high pressure problem, and this phrase confuses it with the high pressure observed in steady-state conditions	The sentence "It is a proven fact that breakages are three times higher in intermittent supply water systems over a one-year period (Charalambous 2011)" has been removed in order to avoid confusions.
Page 4, line 7 – the terms "pressure" and "energy" are confusingly used	The sentence "Since the layout of the system conditions energy efficiency, pressure management should begin at the design stage" is now "Since the energy efficiency of a water network is conditioned by its layout, pressure management should begin at the design stage"
Page 4, line 24 – the difference between EMA, PMZ and DMA should be highlighted at some point. If the authors consider the same, only one abbreviation should be used	Concerning this comment, the sentence "The differences among EMAs, PMZs and DMAs have been previously discussed (Cabrera et al., 2019)" has been added to the text.
Page 4, line 61 – the term "structural losses" is used for the first time in the introduction. It has to be defined before.	As this term is also mentioned in the abstract, the sentence "structural losses (derived from topographic energy)" has been added. Later, the first time that it is mentioned in the introduction, the reference in which the concept is explained has been included (Cabrera et al. 2019).
2 PRESSURIZED WATER TRANSPORT SYSTEMS. BASIC ENERGY CONCEPTS	
Page 7, line 4 – the term "leaving node" can be understood as a flow through a diverging pipe, so it should be replaced	The term "water leaving node" is now "total volume at node j". The sentence has been modified as follows: "Where $v_{g,j}$ is the total volume at node j, equal to the water demand at node $v_{c,j}$ plus the leaked volume $v_{l,j}$"
Page 7, line 1 – in Eq. (3), how Hhi is defined for a network with multiple sources?	From a source tracing analysis, the percentage of water arriving to each node coming from each source can be known. The new equation 4 clarifies this point.
Page 7, line 49 – in Eq. (5), it is considered that all nodes have the same pressure surplus of the critical node? If so, how this equation is used in networks with multiple sources?	The pressure surplus is the same for all nodes regardless the number of sources of the system. It is a concept strictly linked to the pressure of the critical node and the pressure required (standard value).
Page 9, line 16 – I think the legend and the figure are incorrect. Please verify this or explain this figure better.	The legend of the figure has been corrected and the figure improved. Height and pressure are now indicated with arrows, while the energetic concepts are represented through shaded areas. Figures 1, 2 and 4 have been updated accordingly to maintain uniformity in the work.
3 TOPOGRAPHIC ENERGY BREAKDOWN	
Page 10, line 56 – how these paths are obtained? As the demand changes through the day these paths can change too	Paths are obtained following the water flow. In looped networks, when the demand changes, the water flow may change, and consequently, paths. However, this is not a problem as paths are determined for each instant of time. The text has been modified in order to clarify this concept.

Page 13, line 25 – using the node with maximum energy available to install a PRV and repeat this process after the valve is installed guarantee the best pressure control in the network? Or instead, using intermediary nodes could lead to better results?	The ideal point at which to install a PRV or PAT is the location where the highest amount of manageable topographic energy is accumulated. This node is able to dissipate (or recover) the maximum amount of topographic energy.
Page 13, line 48 – if the tanks are higher, Etr will increase, but also Esr will increase. So, how the indicator rises to 1?	When tanks are located higher that needed, topographic energy will represent a high percentage of the total supplied height. Thus, the indicator is near to 1. The objective of this indicator is to quantify the relevancy of topographic energy in each particular system with the aim of identifying how relevant is topography (irregular terrain). In real networks, a value of 1 is unachievable, as the numerator Etr can never be equal to the denominator Esr=Euo+Etr. This is because Euo cannot be zero while there are nodes demanding flow and pressure. However, the indicator approaches to 1 when the weight of Etr increases compared to Euo. This happens in irregular networks with high elevation differences. The text has been updated after equation 13 for a better comprehension.
4 FACTORS CONDITIONING TOPOGRAPHIC ENERGY TYPES	
Page 15, line 18 – the legend of Fig. 5 must be corrected	This section has been eliminated and the factors conditioning topographic energy have been summarized at the end of section 3.
Page 17, line 38 – the items of the legend can more detailed	This section has been eliminated and the factors conditioning topographic energy have been summarized at the end of section 3.
5 BREAKDOWN OF STRUCTURAL LOSSES LINKED TO LEAKS	
Page 18, line 35 – what operational losses PATs create? From the hydraulic point of view, its operation is equal to a PRV	The objective of a PRV is to remove energy. That is, this device must be, energetically speaking, inefficient, while the objective of a PAT (a hydraulic machine) is to recover energy. The inefficiency of a PAT is an energy that cannot be finally recovered, and therefore, an operational loss. A comment has been added to the text to clarify this point: "If a PAT is installed, on the one hand, operational losses (those of the hydraulic machine) will be included in Efr; on the other hand, the energy the turbine produces must be subtracted from Esr"
6 METHODOLOGY APPLICATION AND GENERALISATION	
It would be interesting to see the results in the following cases: a more complex looped network, a network with multiple sources, the use of PATs instead PRVs	We agree that it will be interesting to present more complex systems. However, as previously stated in the second comment of reviewer 1, this paper aims to present the fundamentals of the methodology. Besides, as the associate editor comments, there is not enough space for explaining a complex model in this work. Once the theoretical concepts have been explained with clear examples, complex cases can be faced. In any case, after the reviewers' comments, it seems evident that this topic has been of great interest to all them, a fact that encourage the authors to face the complete casuistic suggested.
7 CONCLUSIONS	
This section simply summarizes the paper. It should highlight what is the advantages of this energy analysis for design and management of water networks compared to the procedures adopted nowadays	A final paragraph has been added to present the benefits of this methodology.

REVIEWER 2

Comment	Action
The manuscript, entitled "Topographic energy management in water distribution systems", reviews many energy concepts including operational losses and structural losses in Water Distribution Networks (WDNs). The main subject of this paper is about structural losses to improve the efficiency of WDNs by means of Pressure Reducing Valves (PRVs)/Pumps As Turbines (PATs). Two simple networks (branched and looped WDNs) have been selected to examine the efficiency of the proposed approach. I think this manuscript with substantial revisions can be accepted for publication in the journal of Water Resources Management	Thanks for considering this paper as suitable if improvements are made. In the reviewed version we have considered all the reviewer's comments.
C1) In this paper, to calculate Zh,j→k and pmin,j→k, the possible paths between nodes j and k should be identified. In simple WDNs, it is easy to specify these paths. I think because of the existence of several loops in many real WDNs, it is too difficult to identify these paths without any proper algorithm or software. In this paper, two very simple WDNs have been studied. The authors should illustrate the efficiency of the proposed approach in a more complex WDN by means of a suitable algorithm.	We have added some paragraphs in which we consider this reviewer's main objection. Basically, we state: ▪ We fully agree that is crucial to evidence that the approach is general and, therefore, it can be easily extended to real networks. However, the main aim of this paper is to introduce a new methodology and concepts. For the sake of clarity, the readers must focus on what is new, and novelties can be explained better with simplified examples. In addition, a complex network is not easily to illustrated and needs to be carefully explained. In this case, we are very limited by the paper's size. ▪ The authors had already developed an algorithm in order to identify water paths in complex WDN. It works with both branched and looped networks. Nevertheless, it has not been presented in this work as the identification of paths is complimentary, not being part of the focus of this study. The limit of space and the complexity of the algorithm made unfeasible its presentation in this work. With the objective of clarifying how paths are determined automatically, the main points linked to the algorithm are outlined in the section 3.
C2) The results of this paper is highly correlated to the obtained nodal pressures and nodal discharges. The authors of this paper take advantage of EPANET software to simulate the hydraulic behavior of the system. Since this software doesn't consider the relationship between nodal pressures and nodal discharges, why the authors didn't use other algorithms and software such as WaterGEMS?	In the section 5.1 of the paper this fact is mentioned: "Hydraulic calculations are carried out using EPANET; therefore, the results are obtained assuming a demand-driven approach for user consumption, while leaks (loaded as emitters) are considered pressure-driven demand. Nevertheless, this nodal structural loss audit could be improved with a global pressure-driven formulation (Ciaponi and Creaco, 2018). The proposed structural losses audit could be performed from any of these two perspectives. Nevertheless, regardless of the approach followed, both the concepts explained and the methodology followed would not change."
C3) In page 22, line 30, the authors stated that "adjusting the pump speed is more efficient than installing a PRV" in case study 1. On what basis did the authors change the speed of the pump? What is its new speed? Did the authors make scenarios to achieve the best results? These explanations should be added to the manuscript to let the readers follow the results.	The following paragraph has been added in the paper: "By reducing the relative speed of the pump to 0.976, the pressure at the critical node equals to the required pressure. This is more efficient than installing PRV since, with this action, the Eer is eliminated, being the Esr lower. (ΔE_{sr} =2.29 kWh/h)." If a PRV is installed, the energy is also reduced. However, it is dissipated as friction energy. Therefore, ΔE_{sr} would be lower.

C4) Table 2, for node N1, 78.54 mWc is the head of the node not its pressure. The pressure is 28.54 (mWc). pj (28.54 mWc) + elevation (50 mWc) = head (78.54 mWc)	Thank you for pointing us this error. The mistake is in the height of the node N1 that should be 0m instead of 50m. This node is just after the pump's outlet and has its same height (0m). This has been changed in the current table 1.
C5) In case study 2, the total head of N1 is 200 m but it seems Efr (in Table 7) is calculated considering the total head of 250 m. please check the results of this table and provide me with the calculation.	This difference is due to the reference level, which is 50m, corresponding to the node N2 the lowest node in the system. The calculus is correct. Equation 3 has been modified as there was one concept missing, z_l, the height of the lowest node. Now, it has been included. The energy lost due to friction losses in each node is obtained as follows: $E_{fr} = \gamma \sum v_{g,j} \left[H_{hi} - \left((z_j - z_l) + \frac{p_j}{\gamma}\right)\right]$ As the height of lowest node is 50m (node N2), this will be the reference level of the calculus (zl). Therefore, as shown in this equation, to the height of each node (zj), it will be substracted zl. H_{hi} will be 200m at any moment, as it corresponds to the height of node N1. Next, it is shown the calculation for 2 nodes of the system, N2 and N3: For N2 we have that zj=50m. This node is also the lowest one, and, therefore, the reference node. Consequently, zj final will be equal to zj-zl= 0m. v(r,j) is 25.84 l/s = 93,02 m3/h, and the pressure is 142.8 mWc. Thus,: $\mathrm{E_{fr}} = \gamma \sum \mathrm{v_{g,j}} \left[\mathrm{H_{hi}} - \left((\mathrm{z_j} - \mathrm{z_l}) + \frac{\mathrm{p_j}}{\gamma}\right)\right]$ = [9,81·93,02·(200-((50-50)+142.8))]/3600 = 14.5 kWh/h For N3 we have that zj=150m. Consequently, zj final will be equal to zj-zl= 100m. v_(r,j) is 30.43 l/s = 109.55 m3/h, and the pressure is 37.92 mWc. Thus,: $\mathrm{E_{fr}} = \gamma \sum \mathrm{v_{g,j}} \left[\mathrm{H_{hi}} - \left((\mathrm{z_j} - \mathrm{z_l}) + \frac{\mathrm{p_j}}{\gamma}\right)\right]$ = [9,81·109.55·(200-((150-50)+37.92))]/3600 = 18.53 kWh/h
C6) The suitable figure must be provided in section 2 to explain the parameters of the equations	This figure has been improved in order to clarify these concepts. Height and pressure are now indicated with arrows, while the energetic concepts are represented through shaded areas. Figures 1, 2 and 4 have been updated accordingly to maintain uniformity in the work.
C7) The paper is well written in English, but there are some incomprehensible and long sentences in the manuscript. For instance: - Page 2, line 5: "This is recognized in the manuals tackling the challenge of reducing unaccounted water from a general perspective" - Page 4, line 1: "By installing PRVs or PATs the initial balance is altered with a new energy term, equal to the flow through them times the decrease in pressure they produce." - Page 4, line 30: "The result (Q.p) is related to the power required by users, which, extended over a specific period of time, is the energy delivered to users." - Page 6, line 18: "Removing in equation 3 the consumed volume at the corresponding node, that nodal formulation allows a direct calculation of the total contribution of leaks to friction losses." - Page 7, line 15: "Topographic energy is not in itself a loss of energy as is the case of energy lost through operational losses." And also, "However, it is still an inefficiency, and should be corrected as far as is reasonably possible, since it means that more energy that strictly necessary is supplied." - Page 10, line 50: "Reducing it would mean that the required supply pressure would not be reached at nodes located downstream." - Page 11, line 56: "In short, the total volume of all nodes downstream from start node j must be taken into account, and the fact that they are on one of the possible paths leading to node k." - Page 14, line 58: "With a variable source, all of it is excess energy, i.e. losses that can be avoided by regulating the pumping station." - Page 20, line 23: "Table 3 shows the different overall energy balance terms by node" - Page 22, line 7: "For the annual calculation, it (?) must be multiplied by the hours per year the system is operated" - Page 22, line 55: "Once the PRV has been installed, the indicators referring to topographic energy improve." - Page 26, line 8: "Hence, its name, structural losses, to distinguish it to operational losses, is linked to the operation of the system."	The text has been revised in order to fix long sentences. Besides, it has been revised by an English editorial service (Springer Nature Author Services) in order to correct English grammar errors and expressions. Please find attached the Editing Certificate.
This manuscript should be revised by an English native speaker. Using proper position of commas and shortening the sentences could improve the readability of the manuscript. The following mistakes are also should be corrected: - Page 1, line 33: "loses" should be "losses". - Page 3, line 44: "This is mature technology" should be "This is a mature technology" - Page 3, line 53: please change the word "excesive" to "excessive"	The text has been revised by an English editorial service (Springer Nature Author Services) in order to correct English grammar errors and expressions. Please find attached the Editing Certificate.
C1) A term in the format of abbreviations with capitalized letters should be introduced with the full spelling at its first appearance, followed by its abbreviation immediately. In some cases, this manuscript does not follow this rule. For instance: In page 1, line 43 and 44 (abstract) and in page 3, line 1.	Abbreviations have been revised to ensure that on their first appearance the full spelling is available.
C2) If the authors considered the specific weight of water (γ) to be constant, γ can be taken out from the sigma operator in Equations (6), (9), (14).	This change has been included in the paper.
C3) The symbols of variables should be kept constant in the manuscript. In this respect, please apply the following changes if they are applicable:	These changes have been included in the paper.

In Table 2: vj should be vc,j In Table 4: Emt,j should be Emtr,j as in Equation (9) In Table 6: vr,j should be vg,j In Table 6: vj should be vc,j In Table 7: Elr should be Eolr as in Equation (14) In Table 8: Eatr,j should be Eftr,j In Table 8: Emt,j should be Emtr,j In Table 9: Elr should be Eolr as in Equation (14) In Table 9: Emt,j should be Emtr,j	
C4) For figures that contain multiple parts, the title of each part should be on the bottom of each one. Please revise the title of each part in each figure.	In figures with multiple parts it has been included the title in each part of the figures.
C5) In the caption of Figure 1, the description of part (a) should be replaced with the description of part (b). "Graphic energy balance for (a) variable and (b) rigid energy sources"	This change has been included in the paper.
C6) Parts (a) and (b) are not specified in Figure 4 and also they are not explained in the main text of the manuscript	Parts (a) and (b) of this figure have been specified in the figure: (a) managing topographic energy without a PRVs and (b) managing topographic energy with a PRVs. This figure was already explained in the Main text after equation 10.
C7) Is Figure 5 really necessary for this paper? If it should be in this manuscript, the explanation of this figure should be provided in section 4.1. Also, this figure must have the description of parts (a) and (b) in the figure caption.	This section has been removed and the factors conditioning topographic energy have been summarized at the end of section 3.
C8) In Figure 6, there are titles 6b and 6c in the left bottom of each part. These two titles should be deleted.	This section has been removed and the factors conditioning topographic energy have been summarized at the end of section 3.
C9) The caption of Figure 7 should be revised to "Energy in networks with different profiles: a) increasing (without consumption); b) increasing (with uniform consumption); c) decreasing; d) irregular"	This section has been removed and the factors conditioning topographic energy have been summarized at the end of section 3.
C10) In Figure 8 and Figure 9, for the better presentation of WDNs, all the "mm" and the "m" units can be omitted. Instead of "m" and "mm" for each number, two descriptions can be added to these two Figures: "Diameters in mm" and "Lengths in m".	
C11) In page 23 at line 13, the authors mentioned that "Table 6 (similar to Table 2) shows the node and pipe specifications (roughness 0.1 mm) of this network". This table is only about the nodes. Therefore, this sentence should be revised.	This sentence has been revised as suggested and modified as follows: "Table 4 (similar to Table 1) shows the node specifications (roughness 0.1 mm) of this network."
C12) In Table 3 and Table 7, because of the correlations between variables, the results should be rounded at the end of the calculations not at the beginning.	Calculations have been performed with a spreadsheet. Thus, no rounded has been done during this process. Nevertheless, as we have a problem of space in the table that shows the results, we need round to the second figure. In any case, the reviewer is right, because the final result does not match with the partial calculations. Now results have been amended and calculations match.
C13) The names of the nodes in Figure 9 are N1 to N7. The authors should replace the nodes 2 to 7 in Table 7 and Table 8 with N2 to N7	The names of the nodes in Table 7 and Table 8 have been modified as suggested.
C14) It would be better to write descriptions for the first row and the first column of Table (5) and Table (9).	We are aware that it would be easier for the reader. However, they do not fit in the cells due to space limitations. In order to clarify it, in the first column, the name of each of the scenarios has been detailed as: "Initial scenario" and "Final scenario" in Table 3, and "withouth PRV" and "with PRV" in Table 6.
C15) For the better illustration of the results, put the results of Eer in Table 9	The excess energu (Eer) is zero as the system is rigid, as displayed in table 5. In table 6 it has been included a column where indicates that Eer=0, and columns have been reordered in order to coincide with those of table 3 from the case 1. Therefore, with this action authors believe results will be easier to understand.
C16) In Equation (12), Esr is used without any explanation. I think this term of energy should be explained just before section 3.	The term Esr was already used and explained after equation 1: "*The total energy supplied to the system, Esr*," and after equation 12 (13 in the revised paper): "*The first one, represents the percentage of topographic energy Etr in the total energy supplied to the system Esr*." In equation 15, Esr is further explained with more details when the energy balance is exposed.
C17) In page 5, line 37: Explain about Eer together with the other energy concepts.	The excess of energy has to be subtracted in order to avoid it to account as topographic energy. In order to clarify this, the following sentence has been added after equation 7: "The excess energy existing in each node ($E_{er,j}$) must be subtracted to avoid quantifying it as topographic energy".
C18) In page 5, line 42: Please mention that Epr is not considered in this paper.	It has been mentioned: "The first source of losses, Epr, is the one that usually requires closer attention. These losses are obtained directly from different pump characteristic curves. In this work Epr is not considered."
C19) In page 16, line 8: "and each relative maximum (what?) will require individual study."	This section has been removed and the factors conditioning topographic energy have been summarised at the end of section 3. Although it has been removed from the paper, the explanation is the following: In the case of systems as the one displayed in old figure 7b, topographic energy is unavoidable. In the case of systems as the one shown in old figure 7c, topographic energy is manageable. However, in systems in irregular terrains (old figure 7d), it has to be studied for each node the kind of existent energy, and it will depend on the relative highest points of the system.
C20) Provide the references for "top-down approach" in page 2 line 60 and "stablishing EMA" in page 3 line 1.	The reference is Cabrera et al, 2019, and it has already been cited in the requested location.
C21) What does the authors mean by "they" in page 5 and line 11?	The sentence has been modified in order to clarify its meaning.
C22) Page 4, line 48 and 49: "the lowest node" should be "the height of the lowest node" and also, in page 10, line 3: "the highest node" should be "the height of the highest node"	These sentences have been modified: "The height of the lowest node in the system, z_l, is the reference of the system heights."

	“Among all the nodes on the paths flowing between j and k, the height of the highest node of all will be z_(h, j→k). A similar sentence has also been modified in Case 2. The new sentence is: “The height of the lowest node (N2) is taken as the reference”
C23) Page 5, line 55: "vi the volume through pipe i" should be "vi the flow rate in pipe i"	vi is volume as it is calculated as flow rate per time interval. In the first part of the expression it is used the flow rate (qi). When multiplied by the time interval, in the second part of expression 2, it becomes volume.
C24) Page 17, line 12: "energy and excess (?)", in page 17, line 10, "energy and excess (?)", and also in page 6, line 53, "the excess (?)"	This excess is referred to the excess energy (Eer), while the excess of line 53 is referred to excess of pressure. It has been clarified in the main text as follows: Consequently, the operational loss linked to leaks is E_{lr}^{o}, whereas the complementary summand E_{lr}^{te} is included in the topographic energy and **excess energy**. This approach means that we are able to calculate the amount of energy embedded in leaks caused by topographic energy and **excess energy**. “If the energy source is a rigid one, the excess **pressure** at the critical node is a structural loss, which is explained as follows.”

REVIEWER 3

1. Originality: The paper discusses some possible energy efficiency improvements in pressurized water systems. To this aim "topographic" energy is managed, using PRVs and PATs or by network layout improvement at design time. Authors already published several papers on this topic. However, original elements can be found in the applicative examples and in the insights given for the topographic energy break down.	Thank you.
2. Scientific Quality: Concepts, assumptions and methods are well stated and the applicative examples are clear. Nevertheless, some imperfections and inaccuracies are present in the paper and should be revisited.	The paper has been carefully revisited, considering all the reviewer’s suggestions.
3. Relevance to the Field(s) of this Journal: The paper is in agreement with the selected journal targets.	Thank you.
4. Abstract: The problem position, the research carried out and main findings are properly synthesized in the abstract.	Thank you.
5. Introduction: Background information and research problem are well posed. Research objective(s) are correctly delineated.	Thank you.
6. Literature Review: Literature review is appropriate and accurate and reports recent papers concerning the same topic. Several of these papers are from the same Authors.	This point (high number of self-citations) has been underlined previously by the Associate Reviewer in his third comment. As can be seen in our answer to that comment, the number of self-citations have been reduced from 6 to 3.
7. Methodology: The research carried out is well described as well as the conceptual framework. The text is clear and all formulas are explained or suitable references are provided. Examples are clear and instructive for the reader.	Thank you.
8. Results and Conclusions: The paper states that structural losses should be reduced at design stage. But only a limited part can be managed when system is in operation. However, some synthetic metrics are need to understand how much of such energy can recovered or removed. The proposed nodal energy analysis is firstly applied to a branched and then to a looped network. It seems applicable to both the two kind of networks and examples results encourage for further research effort on this topic, mainly for more complex network layouts.	All reviewers have a similar comment. Due to the interest this topic has raised, authors have been encouraged to present more complex networks in further works.
9. References / Bibliography: It is advisable to reduce the number of self-citations.	As previously commented, they have been reduced from 6 to 3.
10. Figures: Some figures have some inaccuracies mainly in the units of the variables represented in the pictures. For instance, in figure 1 Hhi, which is measured in meters above the reference (energy for weight unit), is compared directly with energy components (Esr, Efr, Eer,...), which, accordingly to the text and formulas, are measured in kJ.	Figures have been corrected and improved in order to clarify the concepts. Height and pressure are now indicated with arrows, while the energetic concepts are represented through shaded areas. Figures 1, 2 and 4 have been updated accordingly to maintain uniformity in the work.
11. Reviewer's Decision Comment: the paper is suitable for publication but some minor corrections should be done	We think that the corrected paper considers all points mentioned by editors and reviewers.
MINOR CORRECTIONS:	
1. Formulas 1 to 10, 14, 15: To get better readability it is advisable make explicit the summation index;	It has been explained in Equation 1. The summation makes reference to all nodes from j=1 to j=n, being n the number of nodes. The index has been included in all these equations.
2. pag 6, row 11 and 18: review "header height". Hydraulic head is a more appropriate term;	These sentences have been modified: “hydraulic head”
3. pag 6, row 32: "higher or lower degrees of" this specification seems unnecessary;	The sentence has been modified by deleting these specifications: “These losses are located in pumping stations, Epr, in pipes as a result of friction, Efr, and through leaks, Elr.”
4. pag 9: review caption of Fig.1. Descriptions of the pictorial schemes should be reversed;	This change has been included in the paper.
5. pag 9: review figure (Fig. 1) in order to compare variables expressed in the same measurement units;	Figure 1 has been improved in order to clarify the concepts. Height and pressure are now indicated with arrows, while the energetic concepts are represented through shaded areas. Figures 1, 2 and 4 have been updated accordingly to maintain uniformity in the work.
6. pag 9, row 43: reference should be revisited. Giugni et al... instead of Guigni et al...;	This reference change has been included in the paper.
7. pag 10: review Fig. 2. See note 5;	Figure 2 has been improved in order to clarify the concepts. Height and pressure are now indicated with arrows, while the energetic concepts are represented through shaded areas. Figures 1, 2 and 4 have been updated accordingly to maintain uniformity in the work.
8. pag 10, rows 29 to 34: review punctuation;	The paper has been carefully revisited, included punctuation.

	The text has been revised by an English editorial service (Springer Nature Author Services) in order to correct English grammar errors and expressions. Please find attached the Editing Certificate.
9. pag 10, rows 41: elevation seems more appropriate than height;	This part of the paper has been deleted due to length restrictions.
10. pag 12, formula 10: explicit summation index seems necessary for a more clear readability.	This change has been included in the paper. The summation is from j=j to j=k, being j the studied node and k the node at the end of the path that carries water from j.
11. pag 13: review Fig. 4. See note 5;	Figure 4 has been improved in order to clarify the concepts. Height and pressure are now indicated with arrows, while the energetic concepts are represented through shaded areas. Figures 1, 2 and 4 have been updated accordingly to maintain uniformity in the work.
12. pag 16: review Fig. 6. See note 5;	This figure and this section have been removed. The factors conditioning topographic energy have been summarised at the end of section 3.
13. pag 16, row 47; statement "where there is uniformly distributed consumption along the pipe" is not in agreement with figure 7b. Energy losses has a non linear behavior in case of uniformly distributed consumption along the pipe.	Figure 7 has been deleted. Nevertheless, the reviewer is right, the energy losses would not be lineal.

TOPOGRAPHIC ENERGY MANAGEMENT IN WATER DISTRIBUTION SYSTEMS

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ABSTRACT

A significant amount of energy is required to operate pressurised water distribution systems, and therefore, improving their efficiency is crucial. Traditionally, more emphasis has been placed on operational losses (pumping inefficiencies, excess leakage or friction in pipes) than on structural (or topographic) losses, which arise because of the irregular (unchangeable) terrain on which the system is located and the network's layout. Hence, modifying the network to adopt an ecologically friendly layout is the only way to reduce structural losses. With the aim of improving the management of water distribution systems and optimising their energy use, this work audits and classifies water networks' structural losses (derived from topographic energy), which constitutes the main novelty of this paper. Energy can be recovered with PATs (pumps as turbines) or removed through PRVs (pressure reducing valves). The proposed hydraulic analysis clarifies how that energy is used and identifies the most suitable strategy for improving efficiency as locating the most suitable place to install PRVs or PATs. Two examples are discussed to illustrate the relevance of this analysis.

Keywords: topographic energy, water distribution systems, energy efficiency, pressure management, energy balance

1 INTRODUCTION

Pressure management is unanimously qualified as an essential strategy for improving the efficiency of water networks, as is recognised in the manuals tackling the challenge of reducing water losses from a general perspective (EU 2015). Managing pressure in water networks has been the objective of many papers ranging from general reviews to more specific work dealing with the practicalities of how this ambition can be fulfilled (Walski et al. 2006). Any surplus pressure over the level established in supply standards (urban networks) or over the level required by sprinklers or drip feed systems (irrigation networks) only leads to problems, namely, increased leakage and pipe breakage (Lambert et al. 2013), particularly if the pressure is fluctuating (Agathokleous and Christodoulou 2016). In short, any surplus pressure contributes to water and energy inefficiencies and shortens the average lifespan of pipes (Lambert and Thornton 2012). Moreover, it is worth remembering that managing water pressure has other consequences. On the one hand, citizens who are used to a high pressure associate a low water pressure with a relatively poor service quality. On the other hand, water supply companies report lower earnings in conjunction with lower consumption, which is dependent on the water pressure. In any case, these apparent drawbacks are easily manageable with environmental education.

Since the energy efficiency of a water network is conditioned by its layout, pressure management should begin at the design stage. Dealing with the problem during the design stage (i.e., a top-down approach) and establishing EMAs (energy management areas) (Cabrera et al. 2019), are more effective strategies than modifying an operating system. When a system is already operating, pressure management is implemented as follows:

a) Installing pressure reducing valves (PRVs) to dissipate surplus energy. In addition, by reducing pressure, leaks are minimised, as is the embedded energy, while friction, which is linked to circulating flows, is also reduced (Cabrera et al. 2010). Installing PRVs is the most common method and has been studied in depth concerning its cost, effectiveness and ease of implementation. Different studies have analysed how many PRVs should be installed (Creaco and Franchini 2013), where they should be placed (Saldarriaga and Salcedo 2015) and how to size them (Covelli et al. 2016).

b) Sub-dividing the network into pressure management zones (PMZs) in an attempt to operate them as district metered areas (DMAs) (Lambert et al. 2013). Creating PMZs is highly dependent on the initial network layout (Castro Gama et al. 2014). The differences among EMAs, PMZs and DMAs have been previously discussed (Cabrera et al. 2019).

c) Installing pumps as turbines (PATs). This option maintains the benefits of PRVs (Patelis et al. 2017) and recovers energy, an advantage that compensates for the complexity involved in regulating a hydraulic machine (in which the flow rates are highly variable over time). However, integrating the generated energy into the electricity loop is not a simple matter, and therefore, this approach is usually used for self-consumption. Installing PATs in optimum places obeys criteria similar to those of PRVs (De Paola et al. 2017). This is a mature technology (Fecarotta et al. 2014), although few systems operating at a real scale utilise this option (Muhammetoglu et al. 2017).

In short, we can “reduce”, “recover” or “remove” surplus energy linked to excess pressure (Cabrera et al. 2019). The differences among these strategies are significant. Reducing focuses on pressure (an intensive variable), whereas recovering and removing refer to energy (an extensive variable). Therefore, by modifying the layout, both pressure and structural losses (Cabrera et al. 2019) are reduced at the source. By installing PRVs or PATs, the initial balance is altered with a new energy term, equal to the flow through them times the decrease in pressure they produce.

This paper reviews energy concepts that have already been introduced concerning water distribution systems, particularly the differences between operational and structural losses. This review also updates the terminology related to the energy balance employed in previous papers.

Structural losses, the subject of this paper, are then broken down to assess and manage topographic energy with the aim of improving water transport efficiency. The focus of this proposed comprehensive approach is illustrated in two networks (branched and looped).

Finally, the differences between the traditional approaches and the method suggested in this paper are highlighted. Most of the current methodologies consist of optimisation algorithms (that is, mathematical tools) that seek to minimise pressures and leaks (Creaco and Pezzinga 2018). Our focus straightforwardly aims to minimise structural energy losses. Although structural energy losses are strongly related to pressure and leaks, they are different concepts. Therefore, the proposed method is mainly a physics approach, which can be easily followed in the simple proposed examples. In any case, guidelines to generalise the procedure to complex real systems are duly outlined.

2 PRESSURIZED WATER TRANSPORT SYSTEMS: BASIC ENERGY CONCEPTS

The aim of a pressurised water distribution system is to efficiently deliver the water flow users require (Q) at the established pressure (p). The result (Q·p) is related to the power required by users, which, extended over a specific period of time, is the energy delivered to users. If water is supplied at the pressure established in the standards, the sum of the energy delivered to each user (j) is the minimum energy required by the system E_{uo}:

$$E_{uo} = \gamma \sum_{j=1}^{n} v_{c,j} \left[(z_j - z_l) + \frac{p_{0,j}}{\gamma} \right] \tag{1}$$

where γ is the specific weight of water; *n* is the number of users; j is the index for users, ranging from 1 to n; $v_{c,j}$ is the volume of water consumed at node j during the considered period; z_j the height of node j; and $\frac{p_{0,j}}{\gamma}$ is the minimum supply pressure at node j. The height of the lowest node in the system, z_l, is the reference system height.

The total energy supplied to the system, E_{sr}, is calculated by adding E_{uo} to the energy losses in the system (operational and structural losses). These concepts, in addition to those that will be discussed in this work, have been established in previous works (Cabrera et al. 2010; Cabrera et al. 2015; Cabrera et al. 2019).

2.1 Energy supply sources

Water supply sources inject water into the system, adding a specific amount of energy per unit volume (kWh/m^3), thereby conditioning the energy efficiency of the network. If the established pressure is exceeded at the least favourable node, this leads to system inefficiency.

Depending on whether supply sources are able to regulate the hydraulic head, those sources can be either rigid or variable (Cabrera et al. 2019). Tanks and reservoirs supply gravitational energy to water, and since the height of the supply, H_{hi}, is almost constant (with only small level variations inside the tanks), the hydraulic head cannot be regulated. Tanks and reservoirs are therefore rigid sources. On the other hand, pumps installed with variable-frequency drivers are variable energy sources because the unitary injected energy, H_{hi}, can be adjusted by modifying their operating point.

2.2 Operational losses

Operational losses are those that depend on the operation of the network. These losses are located in pumping stations, E_{pr}, in pipes as a result of friction, E_{fr}, and through leaks, E_{lr}. There are other losses, such as breakages in tanks, in the network itself or in household tanks, all of which are collectively denoted as E_{or}.

The first source of losses, E_{pr}, is the one that usually requires closer attention. These losses are obtained directly from different pump characteristic curves. In this work, E_{pr} is not considered. The second source of losses in the network, that is, friction losses, E_{fr}, is expressed in equation 2 for a given time interval, Δt (Cabrera et al. 2010):

$$E_{fr} = \gamma \sum_{i=1}^{m} q_i \, \Delta h_i \Delta t = \gamma \sum_{i=1}^{m} v_i \, \Delta h_i \tag{2}$$

where q_i is the flow in pipe i; m is the number of pipes; Δh_i is the head loss in pipe i; and v_i is the volume through pipe i in the given time interval. Nevertheless, as the energy balance is nodal, it is worth expressing friction losses in terms of nodes, leading to the following:

$$E_{fr} = \gamma \sum_{j=1}^{n} v_{g,j} \left[H_{hi} - \left((z_j - z_l) + \frac{p_j}{\gamma} \right) \right] \tag{3}$$

where $v_{g,j}$ is the total volume at node j, equal to the water demand at node $v_{c,j}$ plus the leaked volume $v_{l,j}$ through half of the pipes converging at node ($v_{g,j} = v_{c,j} + v_{l,j}$), while $\frac{p_j}{\gamma}$ is the pressure at node j. Equation 3 therefore provides the friction losses occurring between the source and each node for the total volume of water in each of the nodes. Analytically, equations 2 and 3 give the same result. Removing the consumed volume at the corresponding node from equation 3, the nodal formulation allows a direct calculation of the total contribution of leaks to friction losses.

In systems with multiple sources, the percentage of water that arrives at each node from any of the sources must be known. In this case, the nodal friction E_{fr} should be calculated by weighting, according to each source, the friction corresponding to the water volume at each node, as stated in equation 4:

$$E_{fr} = \gamma \sum_{j=1}^{n} \sum_{s=1}^{k} \alpha_{s,j} \, v_{g,j} \left[H_{hi,s} - \left((z_j - z_l) + \frac{p_j}{\gamma} \right) \right] \tag{4}$$

where $\alpha_{s,j}$ is the percentage of water arriving at node j coming from source s; $H_{hi,s}$ is the piezometric head of the corresponding source s; and k is the number of sources. In what follows, we assume systems with only one source.

On the other hand, the embedded energy in leaks (E_{lr}) is equal to the leaked volume by the piezometric height at the node where the leak is located. This leads to the following nodal equation:

$$E_{lr} = \gamma \sum_{j=1}^{n} v_{l,j} \left[(z_j - z_l) + \frac{p_j}{\gamma} \right] \tag{5}$$

Finally, if the supply is coming from a variable source and there is an excess pressure at the critical node, this is attributed to a deficient pumping regulation, as the energy requirements have not been adjusted to the critical node needs. This energy surplus, E_{er}, is therefore an operational loss, as shown in Fig. 1a. The value for this loss is obtained as follows:

$$E_{er} = \gamma \sum_{j=1}^{n} v_{g,j} \left(\frac{p_{min}}{\gamma} - \frac{p_{0,j}}{\gamma} \right) \tag{6}$$

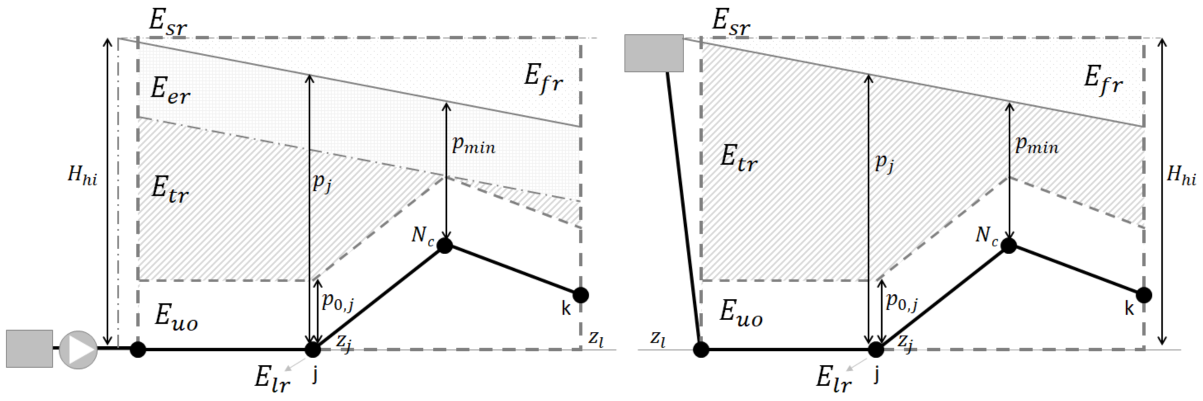
where $\frac{p_{min}}{\gamma}$ is the minimum pressure in the system. If the energy source is a rigid source, the excess pressure at the critical node is a structural loss, which is explained as follows.

2.3 Structural losses: topographic energy

While operational losses depend on how the system is managed, structural losses are inherent to the topography and layout (network, tank heights, etc.). Since users are located at different heights, to supply the right pressure to the critical node, the remaining nodes are supplied at a pressure over the required minimum. Consequently, more energy will be delivered than is required. Topographic energy (E_{tr}) is basically excess energy linked to the topography and network structure, as its name suggests (Cabrera et al. 2015). Topographic energy is not in itself a loss of energy, as is the case of energy lost through operational losses. However, topographic energy is still an inefficiency and should be corrected as far as is reasonably possible since it means that more energy is supplied than is strictly necessary. The value of topographic energy is obtained as follows:

$$E_{tr} = \gamma \sum_{j=1}^{n} v_{g,j} \left(\frac{p_j}{\gamma} - \frac{p_{0,j}}{\gamma} \right) - E_{er,j} \tag{7}$$

The excess energy existing in each node, $E_{er,j}$, must be subtracted to avoid quantifying it as topographic energy. Tanks (as with any rigid energy source) lead to inefficiencies since they are unable to adapt to the exact energy requirements at the critical node over time. In the best-case scenario, with the height being designed to avoid excesses at the least favourable node during peak hours, as demand falls, there will be an energy excess (inefficiency) at the critical point. While pumps can be regulated, tanks cannot (they have small level variations that are not used to regulate the pressure within the system). Consequently, energy surpluses are considered inevitable. Fig. 1 illustrates the difference (Fig. 1a shows the situation for a variable source, while Fig. 1b shows that for a rigid source).



(a) Variable energy sources **(b)** Rigid energy sources

Fig. 1 Graphic illustrations of the energy balance for (a) variable and (b) rigid energy sources

Finally, it must be stated that operational and structural losses are coupled. The former depend on the hydraulic gradient (variable over time), which in turn conditions the latter. Therefore, overall optimisation requires a comprehensive analysis.

3 TOPOGRAPHIC ENERGY BREAKDOWN

To reduce topographic energy as far as possible without compromising the supply pressure at nodes, topographic energy should be broken down into three categories: unavoidable (E_{tr}^{u}), linked to flow (E_{tr}^{f}) and manageable (E_{tr}^{m}), as displayed in Fig. 2. To calculate these components, the downstream path (or paths) of the flow from the analysis node (start point) must be known. This is necessary to guarantee the required supply pressure at all nodes. Hence, a comprehensive analysis of the system is carried out, thus avoiding correction factors (Giugni et al. 2014). The process is described in the following.

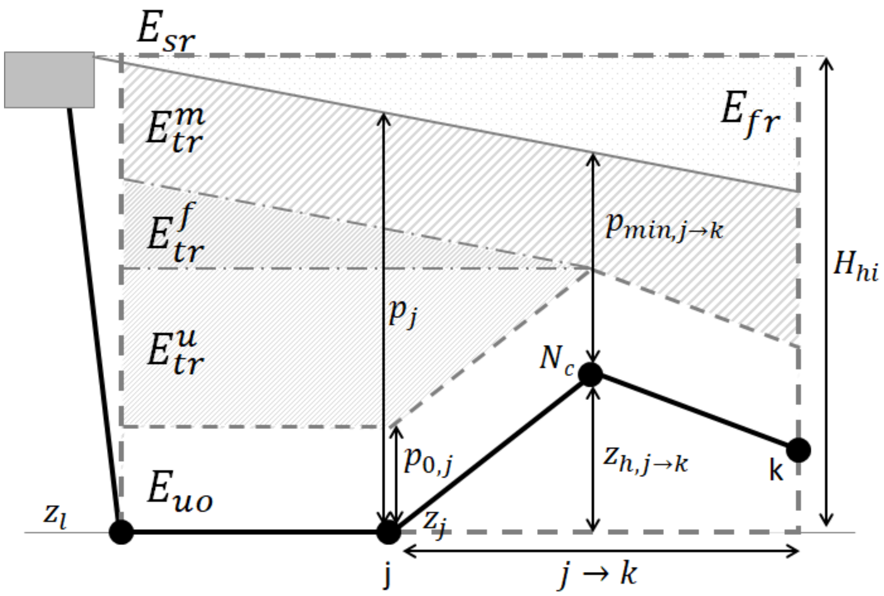


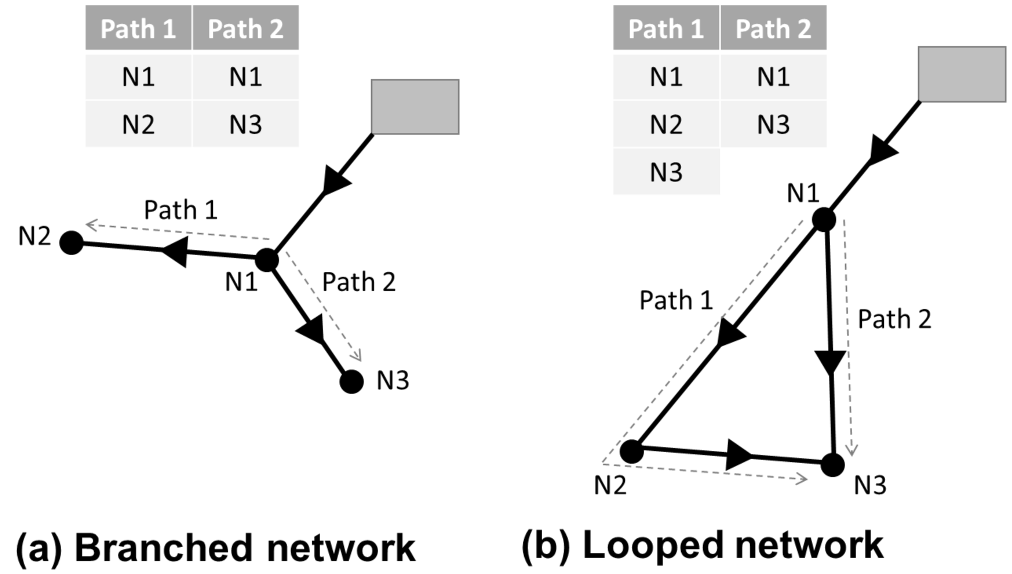
Fig. 2 Topographic energy breakdown with a rigid supply source

3.1 Unavoidable topographic energy

Unavoidable topographic energy is linked to the energy needed to supply a high-elevation point in a network in an ideal situation (no friction losses). Such energy cannot be avoided except by modifying the layout and can be defined as follows:

$$E_{tr}^{u} = \gamma \sum_{j=j}^{k} v_{g,j} \left(z_{h,\, j\to k} - z_{\,j} \right) \qquad (8)$$

where $z_{h,\, j\rightarrow k}$ is the height of the highest node along the possible paths between the study node j and nodes k. The k nodes are the final points of consumption along the paths carrying water downstream from j. In branched networks, the k nodes are always terminal nodes, and there will be as many paths as there are end nodes. Fig. 3a shows that to analyse node N1 (study node j), there are two paths of water downstream from N1 that end at nodes N2 and N3 (the k nodes). In looped networks, the situation is similar, but we need to bear in mind that water can flow down different paths from j to the same k node, and consequently, all of them must be analysed. To analyse node N1 in Fig. 3b, there are two different paths leading to the same k node, i.e., node N3. Among all the nodes along the paths flowing between j and k, the height of the highest node of all will be $z_{h,\, j\rightarrow k}$.



(a) Branched network (b) Looped network

Fig. 3 Possible paths between the study node j and nodes k for (a) a branched network and (b) a looped network

Water paths are obtained following the direction of circulation of the water flow. In branched networks, water always flows in the same direction, and its determination can be simply performed: the flow has only to be followed from the source through the system, and the different paths that appear at bifurcations need to be determined. In looped networks, any change, such as the demand pattern during the day, can impact the water flow direction. This is not difficult with calculus, as paths are determined at each instant of time. For this purpose, the water flow is again followed from the source until it reaches a node where there is a junction of pipes. Any of the pipes in the node creates a new path. Each path ends when it arrives at a node that is already part of the path or when it arrives at a node without any outgoing flow (see node N3 in Fig. 3b). This process of determining paths can be automated once the sense of the water flow is known in each pipe. It requires a hydraulic simulation software package that provides the sense of the water flow.

The unavoidable topographic energy (E_{tr}^{u}) is therefore conditioned by the highest points in the network. At all nodes upstream from the highest point that are located at required heights lower than or equal to this highest point, a part of the topographic energy is unavoidable. Fig. 2 shows how node j has a lower required height than node Nc; therefore, this part of the topographic energy is unavoidable since the flow has to overcome this difference. Unavoidable topographic energy therefore depends on the height differences within the network and the network design.

3.2 Unavoidable flow-dependent topographic energy

This component of the topographic energy is necessary to meet the minimum pressure required at the nodes. Reducing it would mean that the required supply pressure would not be reached at nodes located downstream. This depends on the hydraulic gradient of the system, and consequently, flow-dependent topographic energy, E_{tr}^{f}, is considered:

$$E_{tr}^{f} = \gamma \sum_{j=j}^{k} v_{g,j} \left(z_j + \frac{p_j}{\gamma} - \frac{p_{min,\, j \to k}}{\gamma} - z_{h,\, j \to k} \right) \tag{9}$$

where $p_{min,\, j\rightarrow k}$ is the least favourable node pressure from among the possible paths of flow between study node j and all end nodes k. To assess the minimum pressure between j and k, the midway nodes without demand are not relevant.

3.3 Manageable topographic energy and accumulated topographic energy

The dispensable part of topographic energy is defined as manageable and is equal to:

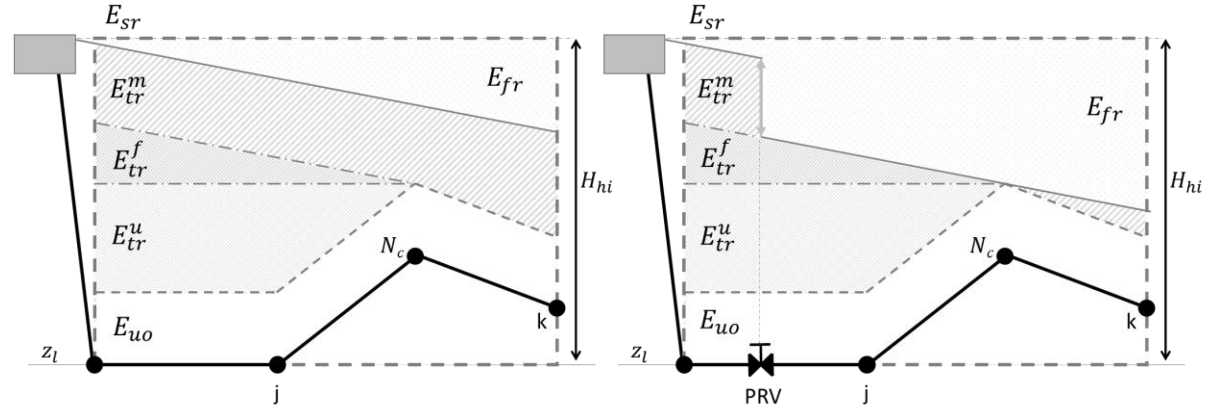
$$E_{tr}^{m} = \gamma \sum_{j=j}^{k} v_{g,j} \left(\frac{p_{min,\, j\rightarrow k}}{\gamma} - \frac{p_{0,j}}{\gamma} \right) - E_{er,j} \tag{10}$$

Manageable topographic energy can be recovered (using PATs) or dissipated (using PRVs). Fig. 4b shows that a PRV introduces a height reduction equal to the dissipated manageable topographic energy to the line of piezometric heights. This manageable topographic energy becomes dissipated energy through friction in the PRV.

Finally, to identify the ideal point at which to install a PRV, the concept of accumulated topographic energy is defined as the total manageable topographic energy pertaining to the path that begins at node j and ends at node k, leading to:

$$\Delta E_{tr,j}^{m} = \gamma \left(\sum_{j=j}^{k} v_{g,j} \right) \left(\frac{p_{min,\, j\rightarrow k}}{\gamma} - \frac{p_{0,j}}{\gamma} \right) - \sum_{j=j}^{k} E_{er,j} \tag{11}$$

The sum includes the total volume $v_{g,j}$ of the nodes along the flow path between study node j and end node k, taking into account that a node can be on more than one path (Fig. 3). In short, the total volume of all nodes downstream from start node j must be considered, as must the fact that all nodes are on one of the possible paths leading to node k. Similarly, we need to consider the sum of the surplus energy between nodes j and k, where applicable.



(a) System without a PRV **(b) System with a PRV**

Fig. 4 Managing topographic energy without a PRV (a) and with a PRV (b)

The ideal point at which to install a PRV or PAT is the location where the highest amount of manageable topographic energy is accumulated. This node is able to dissipate (or recover) the maximum amount of topographic energy. After the first device (PAT or PRV) has been installed, a new study is required to identify where the next device should be installed.

The topographic energy, E_{tr}, can be expressed as:

$$E_{tr} = E_{tr}^{u} + E_{tr}^{f} + E_{tr}^{m} \tag{12}$$

To specify the magnitude and type of topographic energy in the system, two indicators are defined, namely, θ_t and θ_{tm}. The first indicator, θ_t, represents the percentage of topographic energy E_{tr} within the total energy supplied to the system E_{sr}:

$$\theta_t = \frac{E_{tr}}{E_{sr}} \tag{13}$$

If the terrain is very irregular or if tanks are located higher than necessary, this value will be high (θ_t will nearly equal 1), as topographic energy will represent a high percentage of the total energy supplied. In flat networks with energy efficient layouts, θ_t will be closer to 0. Nevertheless, this information is incomplete since it says nothing about whether the topographic energy is manageable. This information is provided by another indicator, θ_{tm}:

$$\theta_{tm} = \frac{E_{tr}^{m}}{E_{tr}} \tag{14}$$

This indicator represents the percentage of manageable topographic energy over the total topographic energy. These two indicators provide relevant (and complementary) information about the system.

It is worth analysing the relationship between topographic energy (and its components) and the features of the system:

a) Influence of the network layout: In systems with supply points located at different heights, topographic energy can be important. Changes in the layout can reduce topographic energy (Cabrera et al. 2019).
b) Influence of the energy source: With a rigid supply source, part of the topographic energy can be managed. With a variable source of energy, if it exists excess energy, it can be avoided by regulating the pumping station.
c) Influence of the system profile: Depending on the profile of the network, topographic energy will be either manageable or unavoidable.

4 BREAKDOWN OF STRUCTURAL LOSSES LINKED TO LEAKS

After having characterised structural losses, we need to discuss some relative aspects of the energy balance. Losses embedded in leaks, E_{lr} (equation 5), are operational losses that are dependent primarily on the water pressure. This term is broken down into two summands. The first includes leaks at standard pressure (E_{lr}^{o}), whereas the second addresses leaks when there is an excess pressure (E_{lr}^{te}), leading to:

$$E_{lr} = \gamma \sum_{j=1}^{n} v_{l,j} \left[(z_j - z_l) + \frac{p_j}{\gamma} \right] = \tag{15}$$

$$= \gamma \sum_{j=1}^{n} v_{l,j} \left[(z_j - z_l) + \frac{p_{o,j}}{\gamma} \right] + \gamma \sum_{j=1}^{n} v_{l,j} \left(\frac{p_j}{\gamma} - \frac{p_{0,j}}{\gamma} \right) = E_{lr}^{o} + E_{lr}^{te}$$

Consequently, the operational loss linked to leaks is E_{lr}^{o}, whereas the complementary summand E_{lr}^{te} is included in the topographic energy and excess energy. This approach means we are able to calculate the amount of energy embedded in leaks caused by topographic energy and excess energy. This leads to the following energy balance:

$$E_{sr} = \gamma \left(\sum_{j=1}^{n} v_{g,j} \right) H_{hi} = E_{uo} + E_{pr} + E_{fr} + E_{lr}^{o} + E_{er} + E_{tr} \tag{16}$$

Operational losses through pumping E_{pr} and excess energy E_{er} are zero in the case of systems supplied through rigid sources. This balance does not include other types of losses (E_{or}), such as load breakages in tanks.

Installing PRVs modifies the values of these terms. The energy dissipated by PRVs is integrated into E_{fr}, whereas E_{tr} will decrease by the same amount. If a PAT is installed, on the one hand, operational losses (those of the hydraulic machine) will be included in E_{fr}; on the other hand, the energy the turbine produces must be subtracted from E_{sr}, whereas E_{tr} will diminish (energy withdrawn by the PAT).

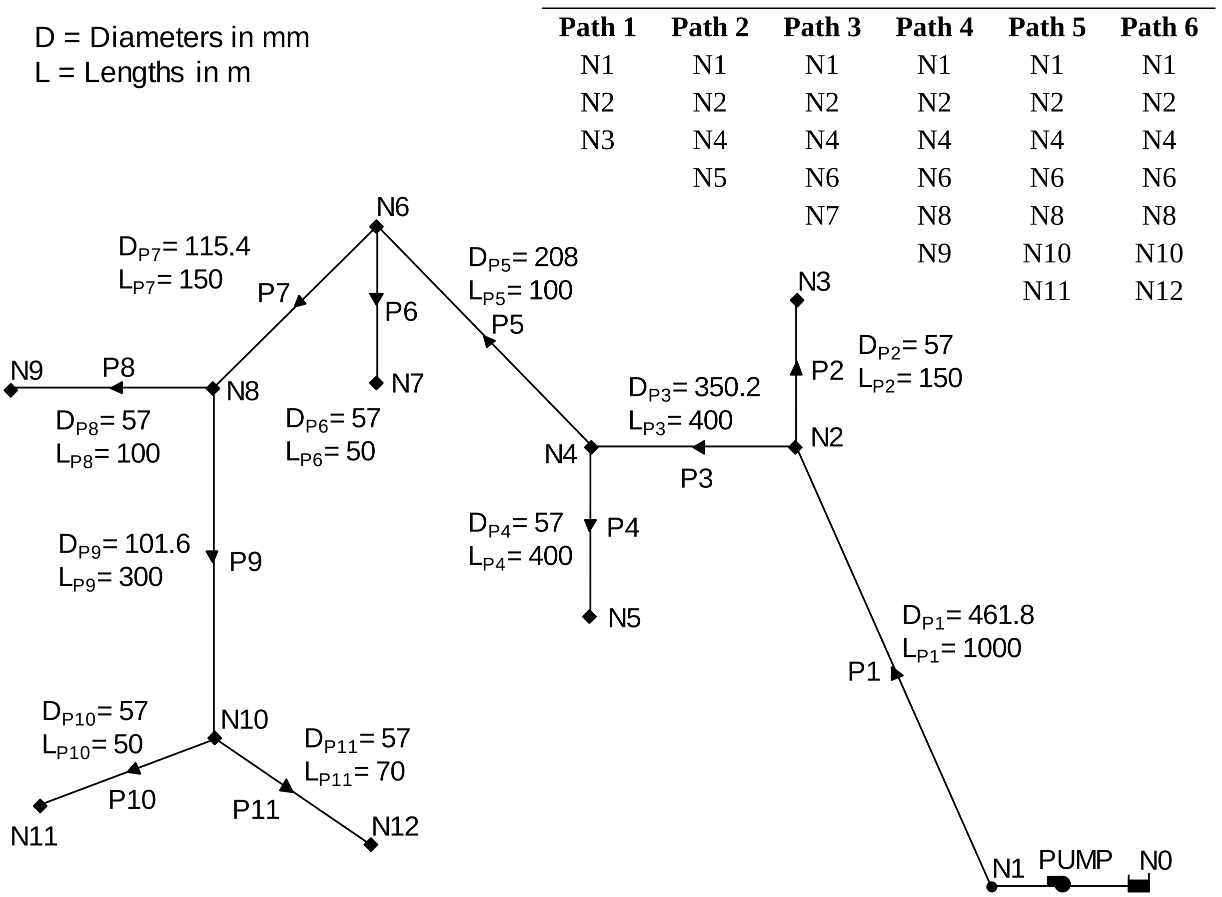
5 METHODOLOGY APPLICATION AND GENERALISATION

The preceding analyses require the flow directions to be known. The minimum pressure required at a node without compromising nodes further downstream can only be determined if the flow direction is known. Therefore, knowing the water path is fundamental. In branched networks, the flow path is immediately formed and does not vary. In looped networks, the paths may depend on the load status of the network. Nevertheless, PRVs and PATs can only be installed in pipes with only one flow direction; therefore, this flow direction must be properly defined. To focus on the discussed concepts, the two example networks are static. In dynamic networks, an analysis is performed for each network status, after which the set of energies is superimposed, and all the results are integrated for the final analysis.

The authors have developed an algorithm to determinate the water paths in both branched and looped networks that allows complex structural energy audits to be performed. As the focus of this paper is on the new concepts and the proposed procedure, the cases presented are simple to allow the methodology to be better understood.

5.1 Case study 1: branched network

A variable supply source injects water into the branched network of Fig. 5. This figure also includes the pipes' diameters and lengths (with a roughness if 0.1 mm) and different flow paths in the network. There are 6 possible paths through which water can flow, as in branched networks, the number of paths is equal to the number of end nodes. The pump is located at the lowest height (z_l=0 m) and supplies the flow at a pressure of 78.54 mWc (H_{hi} = 78.54 m). No losses at the pumping station are deemed to exist. The reference pressure is 15 m at all consumption nodes ($\frac{p_0}{\gamma}$=15 mWc). Hydraulic calculations are carried out using EPANET; therefore, the results are obtained assuming a demand-driven approach for user consumption, while leaks (loaded as emitters) are considered pressure-driven demand. Nevertheless, this nodal structural loss audit could be improved with a global pressure-driven formulation (Ciaponi and Creaco 2018). The proposed structural losses audit could be performed from any of these two perspectives. Nevertheless, regardless of the approach followed, both the concepts explained and the methodology followed would not change.



Path 1	Path 2	Path 3	Path 4	Path 5	Path 6
N1	N1	N1	N1	N1	N1
N2	N2	N2	N2	N2	N2
N3	N4	N4	N4	N4	N4
	N5	N6	N6	N6	N6
		N7	N8	N8	N8
			N9	N10	N10
				N11	N12

Fig. 5 Branched network with a variable supply source

The node data (height, total demand, consumption and leaks) are shown in the first four columns of Table 1. The final three columns in Table 1 show the following: p_j, the pressure at each node; $z_{h,\, j\rightarrow k}$, the greatest height of the set of nodes, including study node j, which are downstream from study node j on any of the possible paths; and $p_{min,\, j\rightarrow k}$, the minimum pressure resulting from applying identical criteria. Having established the paths, the least favourable node in the network is identified as the one with the least pressure. In this case, the least favourable node is N3 (with a minimum pressure of 20.34 mWc), which, as can be seen, is not the highest node.

Table 1: Node features in the branched network

Node ID	z_j	$v_{g,j}$	$v_{c,j}$	$v_{l,j}$	p_j	$z_{h,\, j\rightarrow k}$	$p_{min,\, j\rightarrow k}$

	(m)	(l/s)	(l/s)	(l/s)	(mWc)	(m)	(mWc)
N3	50	3.97	3.83	0.14	20.34	50	20.34
N2	40	2.98	2.78	0.20	38.44	55	20.34
N4	40	0.20	0	0.20	38.33	55	20.82
N5	25	4.20	4.03	0.17	29.26	25	29.26
N6	55	1.65	1.5	0.15	23.06	55	20.82
N7	45	4.56	4.39	0.17	29.54	45	29.54
N8	45	2.95	2.78	0.17	28.37	45	20.82
N9	45	4.73	4.58	0.15	20.82	45	20.82
N10	15	3.01	2.78	0.23	51.56	15	51.56
N11	10	4.23	4	0.23	53.51	10	53.51
N12	5	4.49	4.25	0.24	56.77	5	56.77
N1	0	0.00	0	0.00	78.54	55	20.34
N0	0	-	-	-	-	-	-

Table 2 shows the different overall energy balance terms by node (pumping losses are not considered) and characterises the system's topographic energy. This table includes the term E_{lr}^{te} (already counted in E_{tr}), a fact that must be taken into account when establishing the sum provided by the overall balance E_{sr}.

Table 2: Energy obtained (nodal and overall) in the network (kWh/h)

Nodes	E_{uo}	E_{fr}	E_{lr}^{o}	E_{lr}^{te}	E_{er}	E_{tr}	$E_{tr,j}^{u}$	$E_{tr,j}^{f}$	$E_{tr,j}^{m}$	$\Delta E_{tr,j}^{m}$	E_{sr}
N3	2.44	0.32	0.09	0.01	0.21	0.00	0.00	0.00	0.00	0.00	3.06
N2	1.50	0.00	0.11	0.05	0.15	0.54	0.44	0.09	0.01	0.10	2.29
N4	0.00	0.00	0.11	0.05	0.00	0.05	0.03	0.00	0.01	0.23	0.15
N5	1.58	1.00	0.07	0.02	0.21	0.38	0.00	0.00	0.38	0.38	3.24
N6	1.03	0.01	0.11	0.01	0.08	0.05	0.00	0.04	0.02	0.19	1.27
N7	2.58	0.18	0.10	0.02	0.23	0.42	0.00	0.00	0.42	0.42	3.52
N8	1.64	0.15	0.10	0.02	0.15	0.24	0.00	0.22	0.02	0.15	2.27
N9	2.70	0.59	0.09	0.01	0.24	0.03	0.00	0.00	0.03	0.03	3.64
N10	0.82	0.35	0.07	0.08	0.15	0.93	0.00	0.00	0.93	3.63	2.32

N11	0.98	0.62	0.06	0.09	0.21	1.39	0.00	0.00	1.39	1.39	3.26
N12	0.83	0.74	0.05	0.10	0.22	1.62	0.00	0.00	1.62	1.62	3.46
Total	**16.10**	**3.96**	**0.96**	**0.46**	**1.85**	**5.65**	**0.47**	**0.35**	**4.83**	**-**	**28.5**

The balance includes excess energy because the minimum pressure, 20.34 mWc, exceeds the required amount, 15 mWc (variable supply source). The difference between these two values is modest because the excess is not significant.

Two actions can be taken to improv the system's efficiency: adjusting the minimum pressure to the established supply requirements (reducing the speed of the pump) and installing a PRV. Table 2 shows where the PRV should be installed, namely, at N10, where more manageable topographic energy is accumulated than at any other node. Table 3 compares the initial and final scenarios after implementing these two improvements. The values are rather modest because of the analysed energy period. An annual calculation must be multiplied by the hours per year the system is operated.

Table 3: Total energy (kWh/h) in the branched network

	E_{uo}	E_{fr}	E_{lr}^{o}	E_{lr}^{te}	E_{er}	E_{tr}	E_{tr}^{u}	E_{tr}^{f}	E_{tr}^{m}	E_{sr}	θ_t	θ_{tm}
Initial scenario	16.10	3.96	0.96	0.46	1.85	5.65	0.47	0.35	4.83	28.5	0.20	0.86
Final scenario	16.10	7.36	0.78	0.12	0	1.96	0.46	0.37	1.13	26.2	0.07	0.58

The following conclusions are drawn from this comparison:

- By reducing the relative speed of the pump to 0.976, the pressure at the critical node equals the required pressure. This is more efficient than installing a PRV since, with this action, the E_{er} term is eliminated, reducing the E_{sr} term (ΔE_{sr} =2.3 kWh/h).
- The contribution of the PRV to energy efficiency is marginal. The reduction in manageable topographic energy (3.70 kWh/h) is compensated by the increase in friction within the PRV (ΔE_{fr} =3.40 kWh/h). The difference between these variations (0.30 kWh/h) is mainly due to the energy reduction linked to leaks, as a reduction in flow rates impacts on lower friction losses.
- Table 2, particularly column $\Delta E_{tr,j}^{m}$, pinpoints the optimum location of the PRV to be installed, in this case, at N10. A second analysis with the PRV installed allows us to identify the optimum point at which to install a second PRV (N7).
- Once the PRV has been installed, the indicators referring to topographic energy improve.

On the basis of the information provided in Table 3, each contribution can be studied individually while passing through intermediate stages (i.e., the pump adjustment without and with a PRV).

5.2 Case study 2: looped network

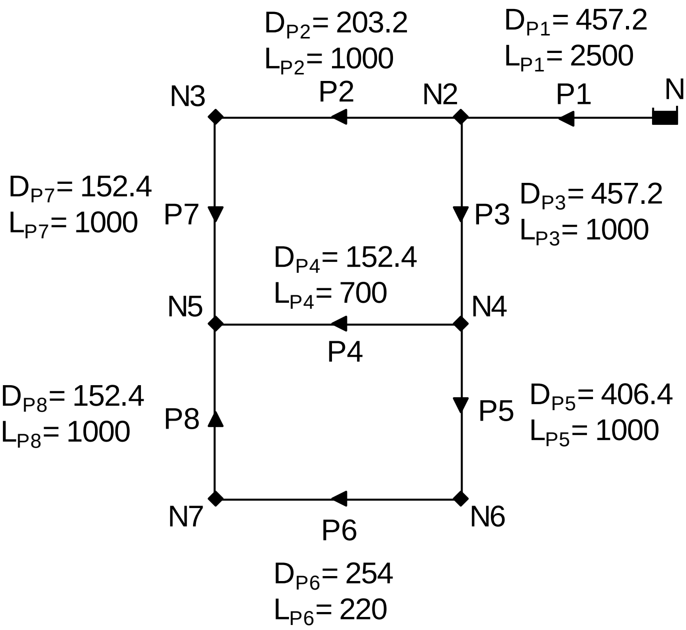
The second example is the looped network depicted in Fig. 6, supplied from a rigid source (N1). The operating pressure is 30 mWc. Table 4 (similar to Table 1) shows the nodes specifications (with a roughness of 0.1 mm) of this network. The arrows show the path of the flow, which is invariable in this load status. The height of the lowest node (N2) is taken as the reference (z_l=50 m).

Table 4: Node features in the looped network

Node ID	z_j	$v_{g,j}$	$v_{c,j}$	$v_{l,j}$	p_j	$z_{h,\, j\to k}$	$p_{min,\, j\to k}$

	(m)	(l/s)	(l/s)	(l/s)	(mWc)	(m)	(mWc)
N2	50	25.84	25	0.84	142.8	150	37.9
N3	150	30.43	30	0.43	37.92	150	37.9
N4	120	30.59	30	0.59	71.25	120	71.3
N5	90	23.69	23	0.69	97.75	90	97.8
N6	80	40.73	40	0.73	109.84	90	97.8
N7	80	60.73	60	0.73	108.51	90	97.8
N1	200	0.00	0	0.00	0.0	200	37.9

N5 is the end of all three possible paths regardless of the path chosen (Fig. 6).



Path 1	**Path 2**	**Path 3**
N1	N1	N1
N2	N2	N2
N3	N4	N4
N5	N5	N6
		N7
		N5

D = Diameters in mm
L = Lengths in m

Fig. 6 Looped network and flow paths

Table 5 shows the nodal and total energy balances (kWh/h), included the topographic energy breakdown. The maximum accumulated topographic value is at node N6, and thus, the PRV should be installed just upstream of N6 and set at 55 mWc, thereby guaranteeing 30 mWc at all nodes (N3 is the critical node).

Table 5: Nodal and total energy balances (kWh/h)

Nodes	E_{uo}	E_{fr}	E_{lr}^{o}	E_{lr}^{te}	E_{er}	E_{tr}	$E_{tr,j}^{u}$	$E_{tr,j}^{f}$	$E_{tr,j}^{m}$	$\Delta E_{tr,j}^{m}$	E_{sr}
N2	7.36	14.50	0.25	0.93	0.00	28.59	25.35	1.24	2.01	16.47	50.70
N3	38.26	18.53	0.55	0.03	0.00	2.36	0.00	0.00	2.36	4.20	59.72
N4	29.43	17.63	0.58	0.24	0.00	12.38	0.00	0.00	12.38	63.02	60.02
N5	15.79	14.47	0.47	0.46	0.00	15.77	0.00	0.00	15.75	15.75	46.48
N6	23.54	24.04	0.43	0.57	0.00	31.90	4.00	0.84	27.07	83.18	79.91
N7	35.32	36.63	0.43	0.56	0.00	46.77	5.96	0.45	40.36	56.11	119.15
Total	**149.70**	**125.80**	**2.71**	**2.79**	**0.00**	**137.77**	**35.31**	**2.53**	**99.93**	**-**	**415.98**

Similar to Table 3, Table 6 compares the energy audits without and with a PRV. The main difference lies in the fact that with the PRV installed, the water flow in line P8 changes its direction, and the new end of the line becomes N7. After the PRV is installed, $\theta_t = 0.19$. If further energy reduction is required, a second PRV can be installed. Any additional analysis should consider the three new paths ending at N7.

Table 6: Total hourly energy (kWh/h) of the looped network with and without a PRV

	E_{uo}	E_{fr}	E_{lr}^{o}	E_{lr}^{te}	E_{er}	E_{tr}	E_{tr}^{u}	E_{tr}^{f}	E_{tr}^{m}	E_{sr}	θ_t	θ_{tm}
Without a PRV	149.7	125.8	2.71	2.79	0	137.77	35.31	2.53	99.93	415.98	0.33	0.73
With a PRV	149.7	185.8	2.35	1.72	0	77.08	25.35	13.82	37.90	414.90	0.19	0.49

As in the preceding example (the branched network), the PRV barely contributes to improving the energy efficiency of the network since the reduction in manageable topographic energy (62.03 kWh/h) is counteracted by a friction increase (60 kWh/h). In this case, as there are fewer leaks in the looped network than in the branched network, the differences are even lower.

7 CONCLUSIONS

The global energy analysis performed in this study from a strictly hydraulic perspective allows topographic energy to be better managed. This energy, although necessary, is inefficient because of the excess pressure over and above the reference value. These losses, called structural losses, should be reduced beginning at the design stage (through an ecologically friendly layout); when a system is already operating, the possibilities to manage these losses are limited. Recovering or removing part of the existing topographic energy are available options. To better understand and assess the improvement possibilities, it is worth breaking topographic energy down into unavoidable, unavoidable flow-dependent and manageable components. Only the third component can be recovered (using PATs) or removed (using PRVs).

From the energy audit of structural losses, the main novelty of this paper, that is, a strategy that should be followed to break down topographic energy based on a nodal energy analysis, is presented. The proposed methodology analyses the energy at each node and performs a downstream comparison through to the end node on the path. The ultimate aim is to calculate the accumulated topographic energy at each node for each load status. The final sum (superimposing all load statuses) indicates all the energy efficiency benefits of installing a PRV (or PAT), including the benefits stemming from reducing leaks. This automated process, based on a hydraulic model, is capable of analysing real networks.

In summary, while the focus of traditional approaches is on minimising leaks and pressures using mathematical optimisation techniques, this new methodology seeks to maximise the system's energy efficiency through a hydraulic procedure. Consequently, final decisions can be made with a clearer view of the system's behaviour.

NOTES:

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Compliance with Ethical Standards

Conflict of Interest: None

Appendix A: Glossary

E_{er}= Energy supplied in excess for the real systems

E_{fr} = Energy dissipated through friction in pipes and valves

E_{lr} = Energy embedded in leaks;

E_{lr}^{te}= Energy embedded in leaks caused by overpressure

E_{or} = Other energy operational losses

E_{pr} = Energy pumping station losses;

E_{sr} = total supplied energy for the real systems

E_{tr} = topographic energy required by the real system

E_{tr}^{f}= flow topographic energy

E_{tr}^{m}= Manageable topographic energy

$\Delta E_{tr,j}^{m}$ = Accumulated manageable topographic energy at node j

E_{tr}^{u}= Unavoidable topographic energy

E_{uo} = minimum required energy by users

H_{hi} = highest piezometric head

$H_{hi,s}$ = piezometric head of the corresponding source s

$p_{0,j}/\gamma$ = required pressure (established by standards) at the generic node j

p_j/γ = pressure at the generic node j

p_{min}/γ = minimum pressure

$p_{min,\, j\rightarrow k}/\gamma$ = minimum pressure between nodes j and k

$v_{c,j}$ = volume demand at node j

$v_{l,j}$ = volume leakage at node j

$v_{g,j}$ = total volume at node j = $v_{c,j} + v_{l,j}$.

z_j = Elevation of node j

$z_{h,\, j\rightarrow k}$= highest node elevation between nodes j and k

z_l = lowest node elevation

$\alpha_{s,j}$= percentage of water arriving at the node j that comes from source s

γ = water specific weight

θ_t = percentage of total topographic energy = E_{tr}/E_{sr}

θ_{tm}= percentage of manageable topographic energy; real case = $\frac{E_{tr}^{m}}{E_{tr}}$

REFERENCES

Agathokleous A, Christodoulou S (2016) Vulnerability of Urban Water Distribution Networks under Intermittent Water Supply Operations. Water Resources Management 30: 4731–4750. https://doi.org/10.1007/s11269-016-1450-3

Cabrera E, Pardo MA, Cobacho R, Cabrera E (2010) Energy Audit of Water Networks. Journal of Water Resources Planning and Management 136(6): 669–677. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000077

Cabrera E, Gómez E, Cabrera E, Soriano J, Espert V (2015) Energy assessment of pressurized water systems. Journal of Water Resources Planning Management 141(8): 04014095. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000494

Cabrera E, Gómez E, Soriano J, del Teso R (2019) Towards eco-layouts in water distribution systems. Journal of Water Resources Planning and Management 145(1): 04018088. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001024

Castro Gama ME, Quan P, Andreja J, Chiesa C (2014) Model-Based Sectorization Of Water Distribution Networks For Increased Energy Efficiency. 11th International Conference on Hydroinformatics. HIC 2014, New York City, USA

Ciaponi C, Creaco E (2018) Comparison of Pressure-Driven Formulations for WDN Simulation. Water 10(4): 523. doi:10.3390/w10040523

Covelli C, Cozzolino L, Cimorelli L, Della Morte R, Pianese D (2016) Optimal Location and Setting of PRVs in WDS for Leakage Minimization. Water Resources Management 30(5): 1803–1817. https://doi.org/10.1007/s11269-016-1252-7

Creaco E, Franchini M (2013) A new algorithm for real-time pressure control in water distribution networks. Water Supply 13(4): 875-882. https://doi.org/10.2166/ws.2013.074

Creaco E, Pezzinga G (2018) Comparison of Algorithms for the Optimal Location of Control Valves for Leakage Reduction in WDNs. Water 10(4): 466. https://doi.org/10.3390/w10040466

De Paola F, Giugni M, Portolano D (2017) Pressure Management Through Optimal Location and Setting of Valves in Water Distribution Networks Using a Music-Inspired Approach. Water Resources Management 31: 1517. https://doi.org/10.1007/s11269-017-1592-y

EU (European Union) (2015) EU Reference document Good Practices on Leakage Management. Office for Official Publications of the European Communities, 2015. Luxembourg.

Fecarotta O, Aricò C, Carravetta A, Martino R, Ramos H (2014) Hydropower Potential in Water Distribution Networks: Pressure Control by PATs. Water Resources Management 29: 699. https://doi.org/10.1007/s11269-014-0836-3

Giugni M, Fontana N, Ranucci A (2014) Optimal Location of PRVs and Turbines in Water Distribution Systems. Journal of Water Resources Planning and Management 140 (9): 06014004. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000418

Lambert A, Thornton J (2012) Pressure: bursts relationships: Influence of pipe materials, validation of scheme results, and implications of extended asset life. Proc., IWA Int. Specialized Conf. Water Loss 2012, IWA, The Hague, The Netherlands

Lambert A, Fantozzi M, Thornton J (2013) Practical approaches to modelling leakage and pressure management in distribution systems – progress since 2005. CCWI 12th International Conference on Computing and Control for the Water Industry

Muhammetoglu A, Nursen C, Karadirek IE, Muhammetoglu H (2017) Evaluation of performance and environmental benefits of a full-scale pump as turbine system in Antalya water distribution network. Water Supply 18 (1): 130-141. https://doi.org/10.2166/ws.2017.087

Patelis M, Kanakoudis V, Gonelas K (2017) Combining pressure management and energy recovery benefits in a water distribution system installing PATs. Journal of Water Supply: Research and Technology-Aqua 66 (7): 520–527. https://doi.org/10.2166/aqua.2017.018

Saldarriaga J, Salcedo CA (2015) Determination of optimal location and settings of Pressure Reducing Valves in Water Distribution Networks for minimizing water losses. 13th CCWI. Procedia Engineering 119: 973 – 983. https://doi.org/10.1016/j.proeng.2015.08.986

Walski T, Bezts W, Posluszny ET, Weir M, Withman B (2006) Modeling leakage reduction through pressure control. Journal American Water Works Association 98 (4): 147-155. https://doi.org/10.1002/j.1551-8833.2006.tb07642.x

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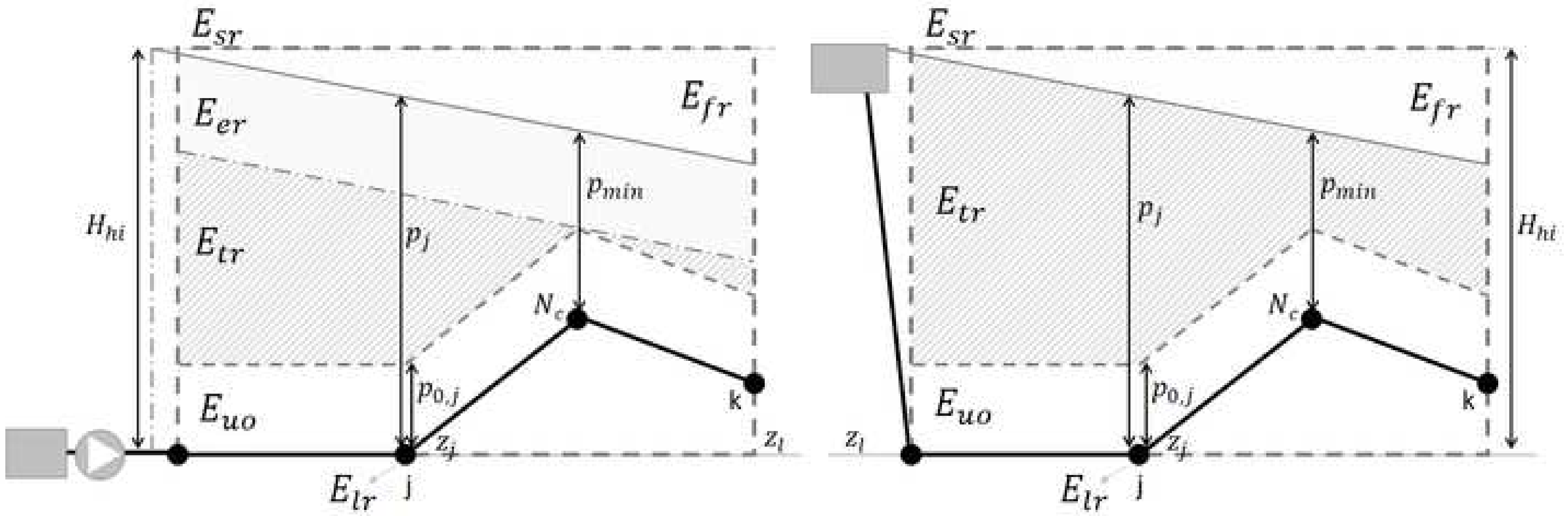
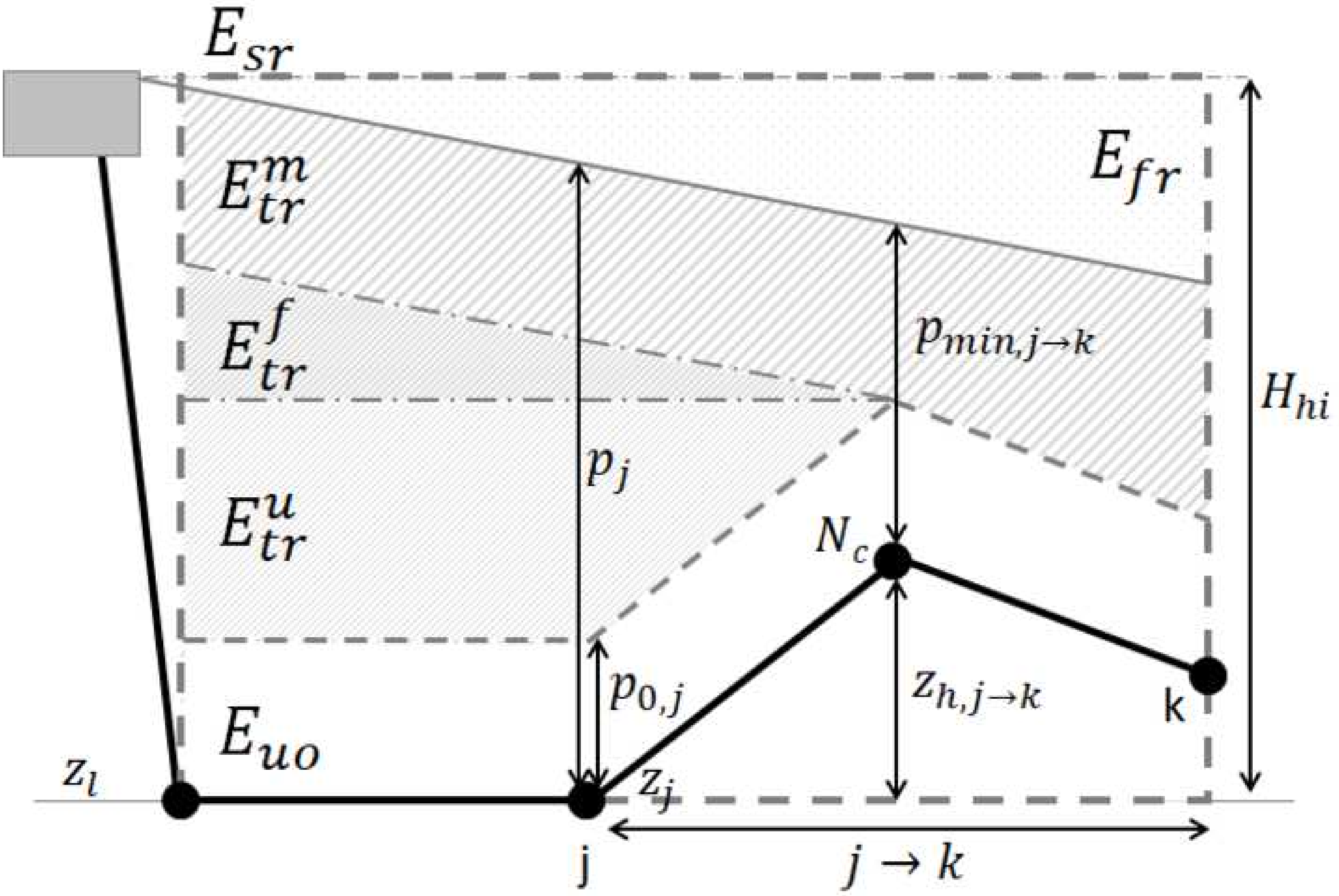
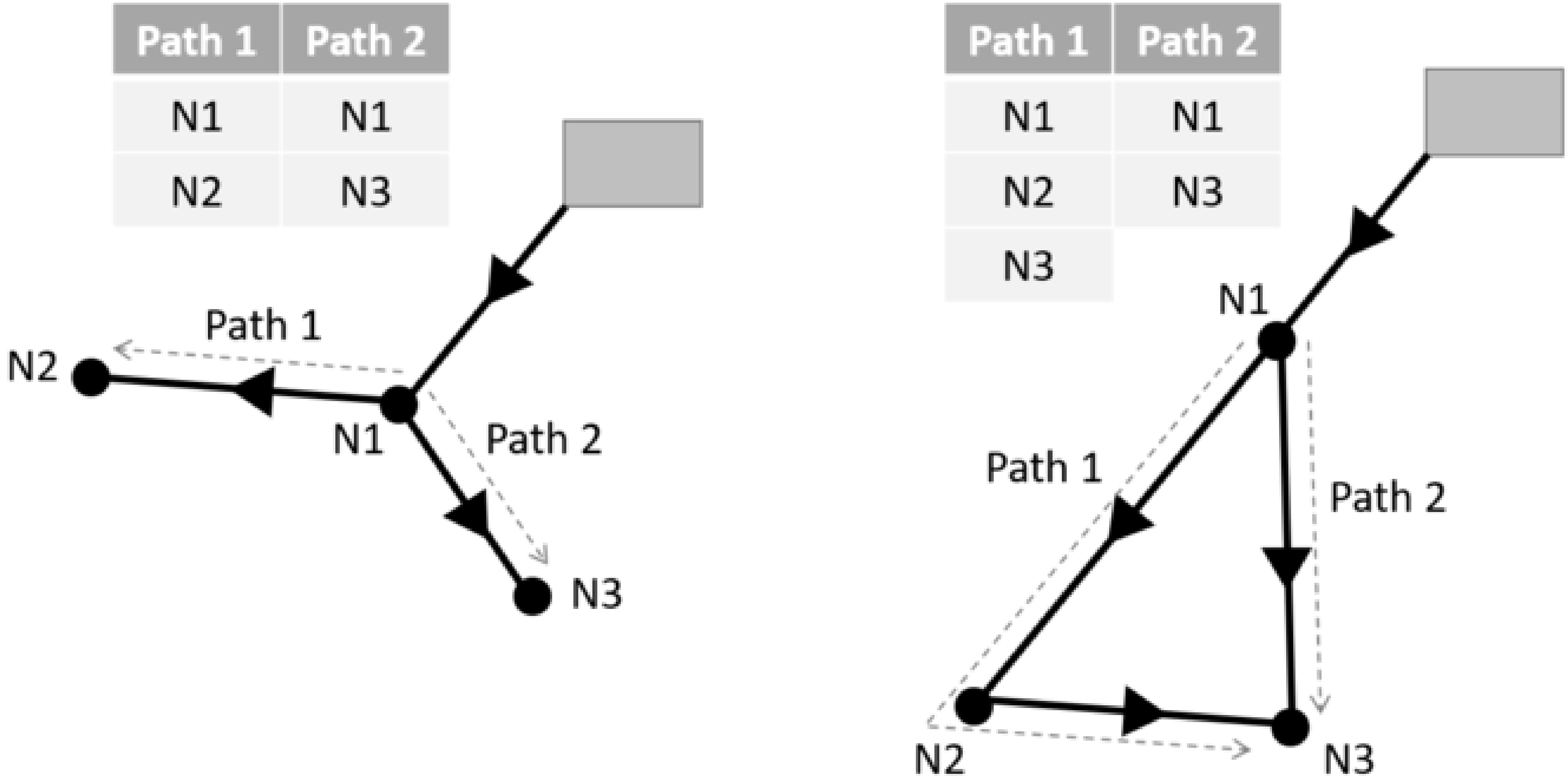
Fig1



(a) Variable energy sources (b) Rigid energy sources


E_{sr}
E_{tr}^{m}
E_{fr}
E_{tr}^{f}
$p_{min,j\rightarrow k}$
H_{hi}
p_j
E_{tr}^{u}
N_c
$p_{0,j}$
$z_{h,j\rightarrow k}$
k
E_{uo}
z_l
z_j
j
$j \rightarrow k$

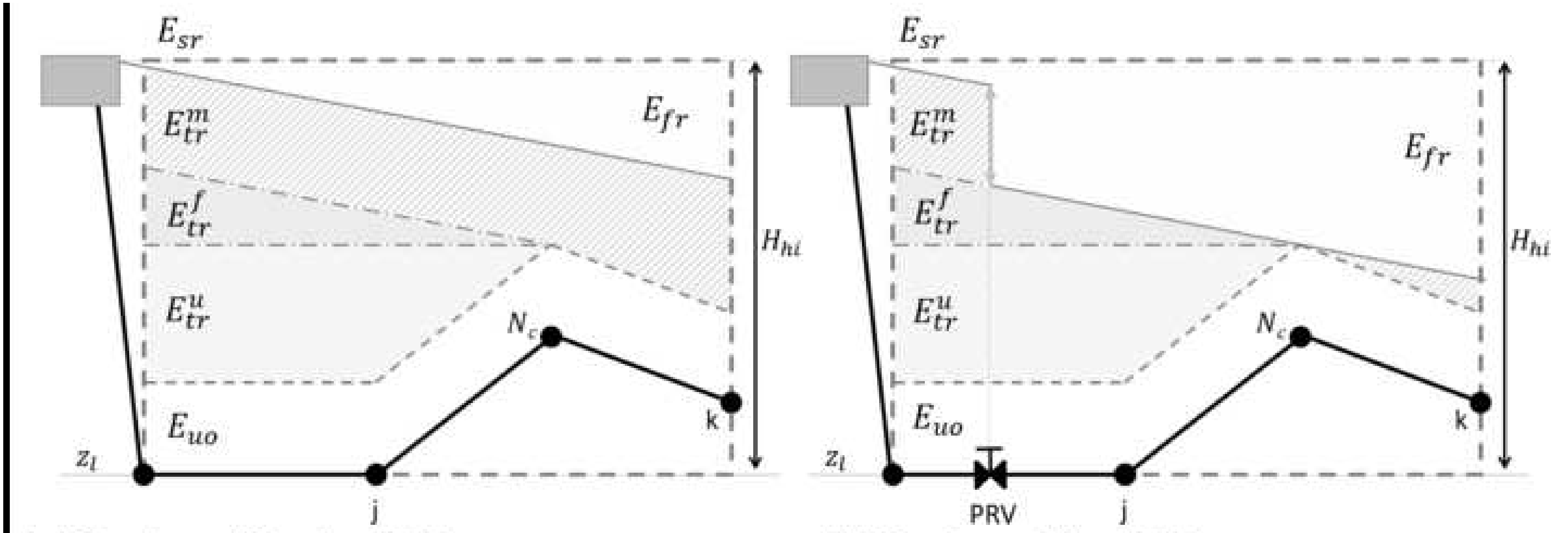


Path 1	Path 2
N1	N1
N2	N3

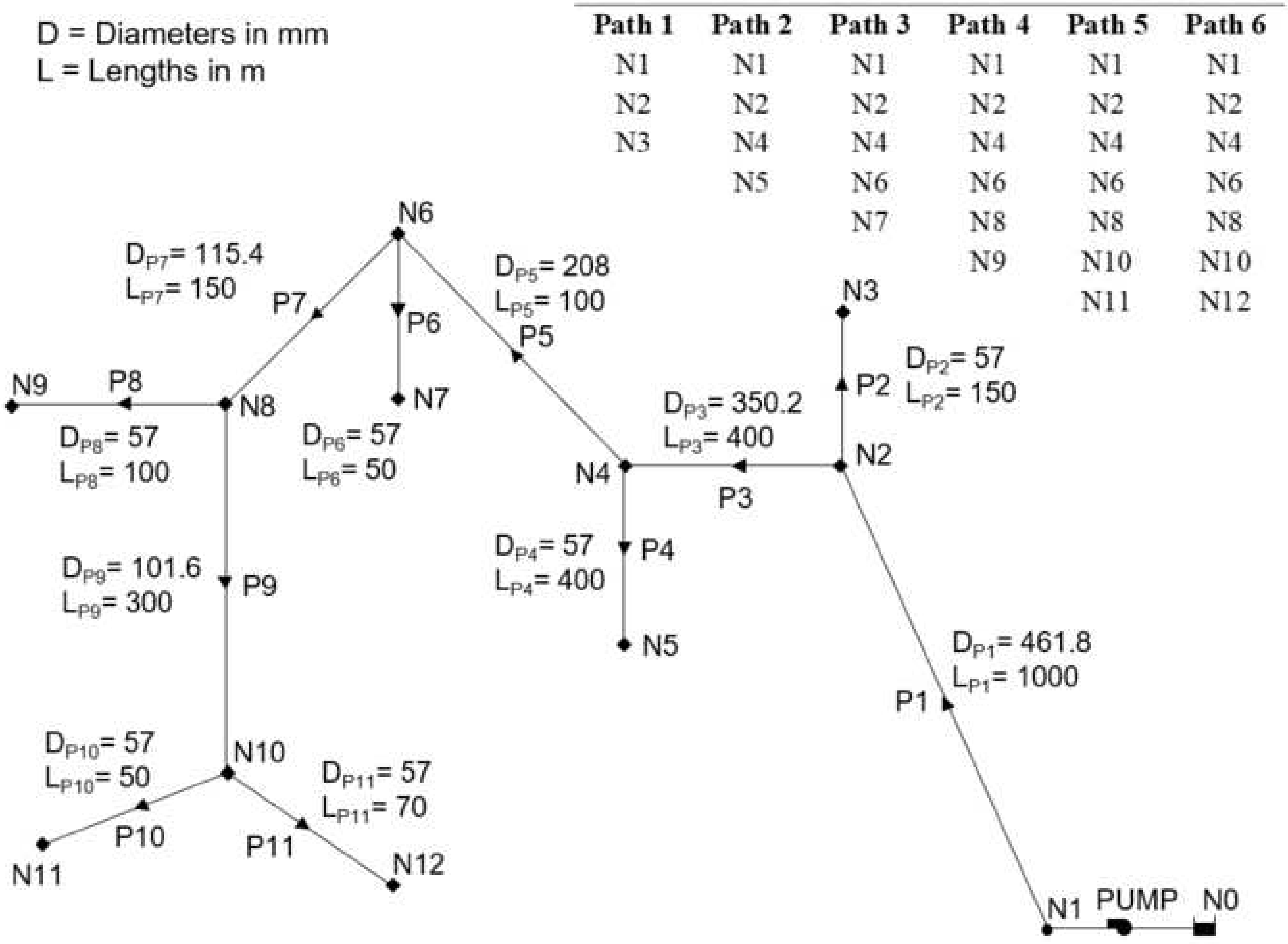
Path 1	Path 2
N1	N1
N2	N3
N3	

(a) Branched network

(b) Looped network

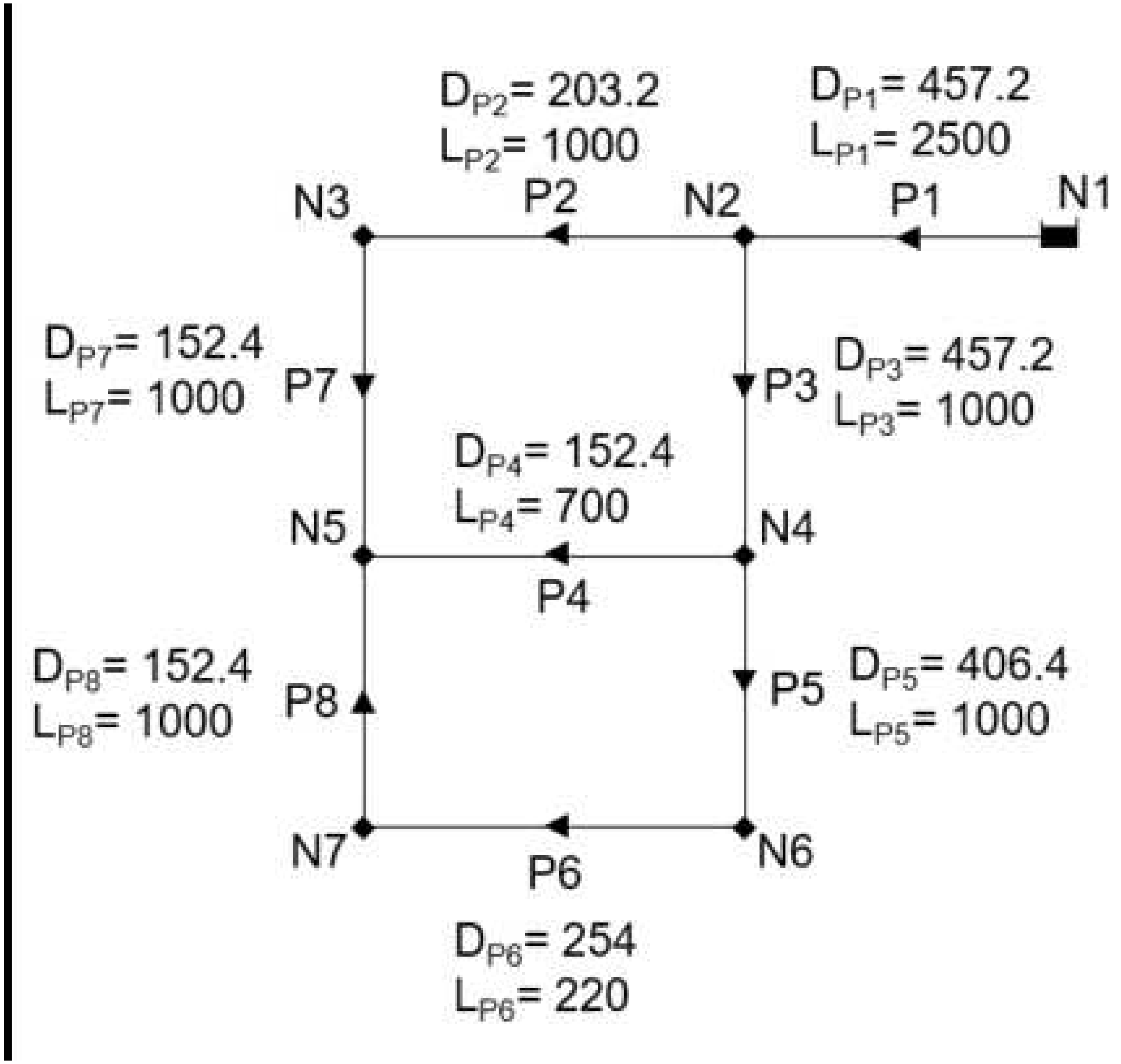


(a) System without a PRV **(b) System with a PRV**



Path 1	**Path 2**	**Path 3**	**Path 4**	**Path 5**	**Path 6**
N1	N1	N1	N1	N1	N1
N2	N2	N2	N2	N2	N2
N3	N4	N4	N4	N4	N4
	N5	N6	N6	N6	N6
		N7	N8	N8	N8
			N9	N10	N10
				N11	N12

Fig6



Path 1	**Path 2**	**Path 3**
N1	N1	N1
N2	N2	N2
N3	N4	N4
N5	N5	N6
		N7
		N5

D = Diameters in mm
L = Lengths in m