PERFORMANCE STUDY OF WATER DISTRIBUTION SYSTEMS BASED ON FLOW PATHS ACCUMULATION

Salah H. A. Saleh and Edawi Wheida

Civil Engineering Department, Faculty of Engineering, University of Tripoli, Libya
Email: salah.saleh@uot.edu.ly

الملخص

تعتمد الطرق التقليدية في تصميم شبكات توزيع المياه على استيفاء الاحتياجات المائية المطلوبة والضغوطات المحددة عند نقاط الاستهلاك شريطة أن تكون كل مكونات الشبكة داخل الخدمة. لكن هناك عدة أسباب تجعل أحد مكونات الشبكة خارج الخدمة لفترة زمنية معينة. فالزيادة المفاجئة في ضغط الشبكة أو الأحمال المرورية الثقيلة قد تؤدي إلى انفجار الأنبوب أو على الأقل حدوث تسريب عند وصلات الأنابيب وبالتالي انقطاع المياه عن بعض المستهلكين إلى حين إصلاح أو استبدال الأنبوب. بناء عليه، فإن التوجه الحالي لمنهجيات تصميم شبكات المياه يهدف إلى الوصول لتصاميم قادرة على أداء وظيفتها تحت الحالات التشغيلية الطبيعية وحالات الأعطال. إن عملية المحاكاة الدقيقة لكل الأعطال الممكن حدوثها للشبكة حتى ولو كانت شبكة صغيرة يعتبر أمرا غير عملي وعملية مستهلكة للوقت والذي يجعل من الضروري إنشاء مقاييس بديلة لتقييم حالات الأعطال بطريقة غير معقدة. تعتبر أنتروبيا الشبكة من ضمن المقاييس التي تم إنشاؤها والتي ترتبط بعلاقة قوية مع طرق المقاييس الدقيقة. إلا أن حساب أنتروبيا الشبكات يتطلب توظيف طرق حل تكرارية لحل معادلات غير خطية في حالة الشبكات متعددة المصادر. تم في هذه الدراسة اقتراح مقياس جديد وسهل الحساب. يعتمد المقياس الجديد على مبدأ تراكم اتجاهات التدفق بالأنابيب فقط ولا يتطلب حل معادلات هيدروليكية وحل معادلات غير خطية. تم الحصول على نتائج محفزة عند تطبيق المقياس المقترح على شبكة مرجعية من أدبيات البحث.

ABSTRACT

Water distribution networks are conventionally designed to satisfy required water demands and prescribed pressures at consumption points conditioned on that all network components are being in service. However, a network component could be unavailable for a certain period due to several reasons. A sudden increase in pressure or heavy traffic loading could result in pipe burst or, at least, leakage at pipe joints, which in turn makes some consumers suffer a shortage of water supply until the pipe is either repaired or replaced. As such, the current trend of water network design approaches aims to produce designs capable of operating under both normal and failure conditions. The fact that the accurate simulation of all possible failures, even for a small network, is a time-consuming and an impractical process makes it essential to establish alternative measures for assessing failure conditions in an uncomplicated manner. Among the established measures, the network entropy has been found to be strongly correlated with accurate measures. However, the evaluation of network entropy involves deploying iterative methods for solving non-linear equations for multiple source networks. In this study, a new and simple to calculate measure is suggested. The new measure is based on the accumulation of pipe flow directions only and does not require solving hydraulic equations and any further non-linear equations. The results are encouraging when applying the suggested measure to benchmark network in literature.

KEYWORDS: Water Distribution Networks; Hydraulic Performance; Network Entropy; Total Flow Paths; Failure Conditions.

INTRODUCTION

Water distribution networks represent an essential infrastructure component that is subject to operational failures, upgrading and rehabilitation processes during operation period. The traditional approach to achieving optimal designs of such systems considers minimizing the construction cost that satisfies the pressure requirements within the system. The resulting designs are characterized with small pipe sizes that have little or no spare capacity to compensate for the effects of component failures or water demand increase. The hydraulic reliability and failure tolerance are considered as measures of network robustness that evaluate the ability of the system to meet water demands under both normal and failure operating conditions. However, these reliability measures are difficult to evaluate [1] and accordingly their inclusion in optimization processes becomes computationally impractical. As a result, several surrogate measures that aim to substantially reduce the computational effort at the cost of accuracy have been suggested. These include network entropy [2], resilience index [3], modified resilience index [4], surplus power factor [5], and recently, pipe hydraulic reliability index [6], probabilistic resilience index [7] and variance of pipe flows [8].

The network entropy, when increased, has revealed to produce designs with improvements in the hydraulic reliability; make use of the arrangements of flow paths in layout optimization [9]; produce high uniformity of pipe diameters in line with increase in the reliability; provide strong positive correlation with hydraulic reliability and failure tolerance [10]; and result in an increase in the overall capacity of the system. However, the fact that flow entropy is highly dependent on pipe flow directions gives rise to some computational issues associated with maximizing entropy of water distribution designs. These particularly include the huge search space of maximum entropy designs, solving a system of non-linear equations for multiple-source systems, and the confinement of the huge solution space into a narrow domain makes very different designs have marginally different flow entropy values.

In this study, a new surrogate measure that addresses the issues is proposed. The new measure uses total flow paths throughout the system as a measure of hydraulic reliability of water distribution systems. The incorporation of the proposed measure into the optimal design of a benchmark network has shown encouraging results. These findings can be summarized in, firstly, the elimination of solving any type of equations in evaluating surrogate hydraulic reliability. Secondly, strong correlation between network entropy and total flow paths. Thirdly, similar values of total flow paths for similar maximum network entropy designs. Finally, very different values of total flow paths for marginally different maximum entropy designs which in turn facilitate recognizing marginally different designs during search process.

FLOW PATHS ACCUMMULATION

To illustrate how total flow paths are calculated for a set of flow directions, four sets of flow directions are presented for simple single-source two-loop network as shown in Figure (1). Unlike branched networks characterized with a unique set of flow directions, looped networks have several sets of flow directions that largely increases with increasing number of loops. However, such sets of flow directions can be determined without the need of solving hydraulic equations and any further non-linear equations as required in other surrogate measures of hydraulic reliability. For example, the determination of network entropy requires pipe flows while resilience index requires nodal pressures, which are both determined from carrying out hydraulic analysis.

The method of calculating total flow paths (TFP) simply starts with counting number of flow paths received by each node. Then, all nodal paths are accumulated for the whole network beginning from the source node until the end node at which flow paths are terminated. For example, the total number of flow paths for cases a, b, c, and d are respectively 9, 8, 8, and 7. Even though the network is small, the resulting total flow paths shows a maximum difference of two flow paths. What about if the network is large and have multiple sources as the situation takes place in real systems.

Evidently, the calculation of total flow paths can be determined directly from the set of flow directions. As such, the incorporation of the proposed measure into an optimization process suggests improving the efficiency of hydraulic reliability evaluation. It should be emphasized that a higher value of TFP implies high distribution of pipe flows (i.e., high uniformity of pipe diameters). The high uniformity of pipe diameters is an important design property because it reduces the hydraulic effects (e.g., pressure deficiency) when a component failure occurs. Accordingly, increasing TFP suggests bringing up an improvement in hydraulic reliability of water networks.

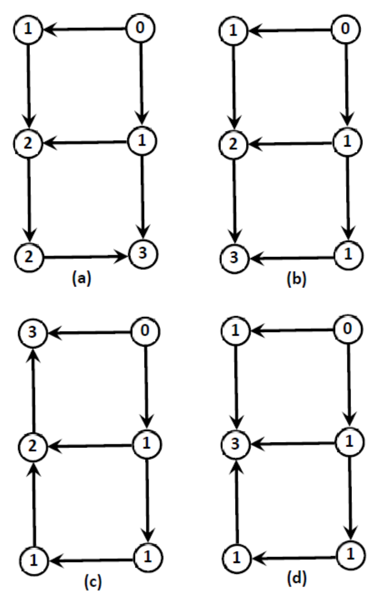

Figure 1: Illustration of flow path accumulation (Circled numbers refer to number of paths passing through each node while zero node represents the network source node)

Model Description

The proposed measure is formulated into an optimization approach to maximize TFP while minimizing both initial cost and hydraulic deficiency. For comparison purposes, another optimization model was formulated in terms of network entropy as a measure of hydraulic reliability in which TFP objective is replaced with maximum entropy (ME) objective. The hydraulic equations were solved by integrating the hydraulic model of EPANET 2 [11] in the optimization model to evaluate hydraulic deficiency using nodal pressures and network entropy using pipe flows for each generated design. The non-dominated sorting genetic algorithm, namely NSGA-II [12], was adopted to drive the optimization process.

The optimization model of the proposed measure minimizes the initial construction cost, hydraulic deficiency, and maximizes total flow paths as follows:

$$f_1 = \sum_{ij} f\left(L_{ij}, D_{ij}\right) \quad (1)$$

$$f_2 = h + (F_g^* - F^*) : , \; h = \sum_i^N max(0, H_i^{req} - H_i) \quad (2)$$

in which N = number of nodes; for pipe ij, L_{ij} = length; D_{ij} = diameter; H_i and H_i^{req} = available and required residual head at demand node i, respectively; F^* = total flow paths; and F_g^* = global maximum number of total flow paths.

Eqs. (1) and (2) show that the computational process of the model is formulated to minimize two objectives: f_1 and f_2. The first objective (f_1) minimizes the initial (Capital) construction cost, while the second minimizes infeasibility that is composed of three terms. The term h in Eq. 2 represents the residual-head infeasibility. If $H_i \geq H_i^{req}$ for all demand nodes, then the solution is hydraulically feasible. The required residual head H_i^{req} is the head at a node above which demands are satisfied in full. H_i^{req} is typically not less than a *minimum* of about 7m [13].

The second term maximizes entropy by minimizing the distance between network entropy and its corresponding maximum value. For each set of flow directions, there is a set of total flow paths (F^*). The model recognizes the set of flow directions to which each solution belongs and accordingly calculates the corresponding number of total flow paths. The third term in Eq. 2 maximizes total flow paths through the minimization of the distance between F^* and F_g^*. F^* approximates the *theoretical* maximum value of entropy for a particular feasible set of *flow directions* while F_g^* approximates the *global* maximum number of total flow paths considering all feasible sets of flow directions. The *global* maximum number of total flow paths is not known *a priori*; our algorithm evolves the *global* maximum number of total flow paths solution by assuming it corresponds to the largest F^* value it has been so far identified, that is F_g^*. The infeasibility measure f_2 seeks feasible solutions that have high values of TFP (a proxy for hydraulic reliability and redundancy). Minimizing the infeasibility measure f_2 promotes the inclusion of a range of solutions with maximum total flow paths for which, *by definition,* F approaches F^*, in the non-dominated set that is augmented by approaching F^* to F_g^*.

Since TFPs result from an accumulation of flow paths at all nodes in a network, it is anticipated that the total flow paths will be of relatively large values and accordingly its contribution in Eq. 2 will be significant. Similarly, solutions with large shortage in pressure will bring up large values and accordingly will have significant contribution to Eq. 2. Therefore, the driving force of the infeasibility objective is to identify solutions with large TFP that are hydraulically feasible. In a probabilistic system, the uncertainty is a maximum if all possible system states or outcomes are equally likely. Conversely, the uncertainty decreases if the probabilities associated with the states or outcomes become more unequal.

The network entropy optimization model minimizes the initial construction cost (Eq. 1), hydraulic infeasibility, and maximizes maximum entropy as explained below.

$$f_2 = h + (S^{\max} - S) + (S_g^{\max} - S^{\max}), \; h = \sum_i \max(0, H_i^{req} - H_i) \quad (3)$$

in which S = entropy; $S^{\max}$ = maximum entropy; and $S_g^{\max}$ = global maximum entropy; and the other terms as defined previously.

Application Network

The proposed measure was applied to a real network that represents the main water system supplying the city of Ferrara-I [14] as shown in Figure (2). The system is a multiple-source network that has 49 nodes, 76 pipes and 29 loops. It is supplied by two reservoirs at nodes 1 and 49. The two reservoirs supply a total demand of 367 l/s and have a total pressure head of 30 m each. All demand nodes are located at a flat region with no difference in elevation. The total length of pipes is about 25,200 m. All pipes have Manning roughness coefficient of 0.015. The design requirements as indicated by the utility operator of this system [14] are that the minimum pressure head at which nodal outflow occurs is 5 m, while the desired head at which nodal demands are satisfied in full is set at 28 m. All pipe diameters are part of the existing system of Ferrara-I. However, the cost of pipe diameter 450 mm was not available in the provided set and determined from the best fit of available pipe sizes.

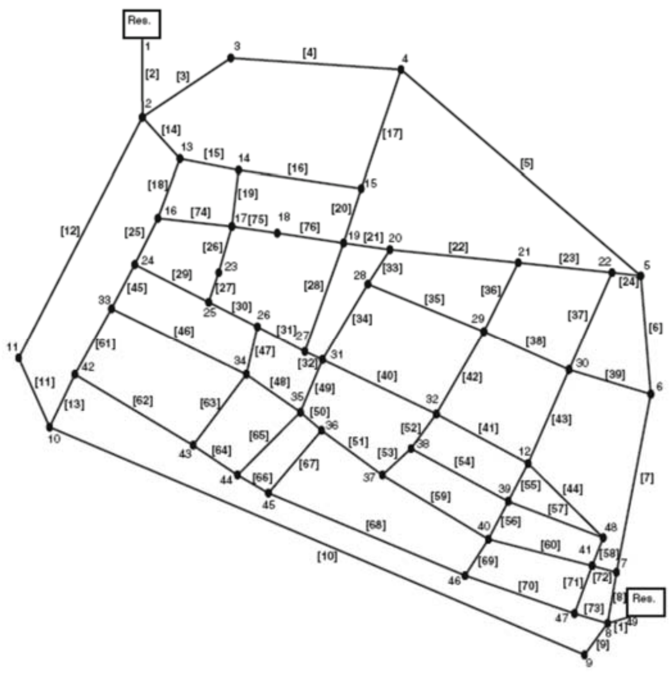

Figure 2: Layout of the application network

RESULTS AND DISCUSSION

The results of the proposed measure are demonstrated in comparison with the ME measure. Different comparative aspects were considered in terms of statistical analysis. Table (1) shows a statistical comparison of the best designs obtained from each measure. Clearly, the proposed measure outperformed the ME measure in terms of physical visualization of results. For example, the identification of performance difference between best and worst designs is best demonstrated in terms of TFP instead of ME.

Table 1: Statistical comparison between the results of the two measures.

Statistical measure	TFP measure	ME measure
Minimum value	115	4.019114
Maximum value	1213	5.012136
Range	1098	0.993022
Standard deviation	225	0.269594

The TFP provides a difference of 1098, while ME provides marginal decimal difference of only 0.993022. If the ME was adopted as a performance measure, it would suggest these designs are very similar in performance. Conversely, the TFP suggests large difference in performance between the two designs. This is also clear from the values of standard deviation in which the TFP produces a wide deviation of 225, while the ME gives a very narrow deviation of 0.269594. The very large range of TFP values reveals an important aspect in terms of optimization. Compared to ME, the suggested measure provides wider search space in which designs are very distinct and thus the optimization approach can recognize designs with very similar ME values. This will bring up the advantage of improving search efficiency and performance of the optimization model.

To demonstrate that the proposed measure approach produces similar designs to the ME measure approach, the best results were shown in Figure (3). Evidently, both approaches produced very similar fronts. The large difference in cost of about 1.5 million units provides a proof that such designs are not similar in performance. This fact is well demonstrated with a difference of TFP of 1098 instead of less than unity in case of using ME.

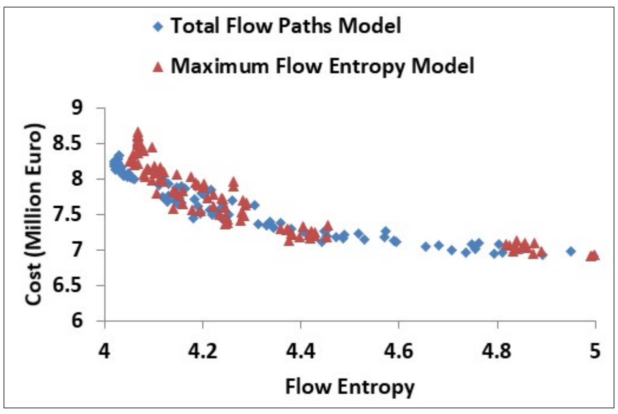

Figure 3: Optimal designs of the two models

Another evidence that the TFP measure can represent the hydraulic performance under failure conditions is clear from the strong correlation with ME as shown in Figure (4). The main finding from this correlation is that the TFP increases with increasing ME, which suggests increasing the hydraulic performance with increasing TFP. The resulting relationship provides another important result: similar ME designs could be largely different in hydraulic performance, which is clear from being having very different TFP values.

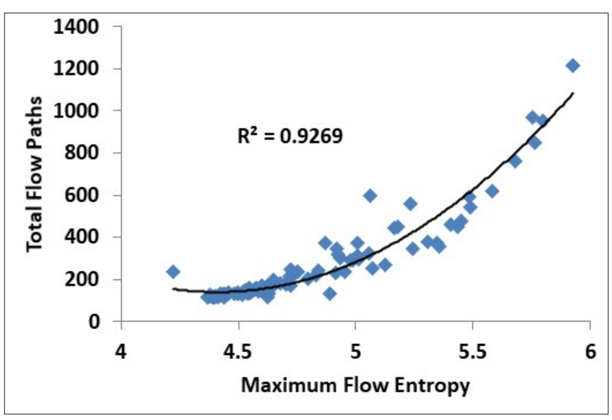

Figure 4: Correlation between TFP and ME

CONCLUSION AND RECOMMENDATIONS

A new measure for assessing hydraulic reliability of water distribution networks has been proposed in this research. The measure is based on the accumulation of total pipe flow paths to increase the number of alternative paths and thus compensating for any hydraulic loss in case of failure conditions. The performance of the suggested measure is assessed in comparison with the network entropy. The two measures were found to be strongly correlated because of application on a benchmark network in literature. The total flow paths measure outperformed the network entropy both computationally and efficiently. The main finding of the study is that the total flow paths provide clear vision and new insights on the differentiation between different designs having very similar entropy values. Since such results are still preliminary, carrying out further investigation on the performance of the suggested measure is highly recommended.

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