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Applying resilience indices for assessing the reliability of water distribution systems

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Abstract: Several indices have been used in the past for the assessment of the performance of water distribution systems. In this paper the performance of water distribution systems is evaluated using the resilience index and the failure index proposed by Todini (2000). The method is demonstrated through the analysis of a real world application, the water distribution system of the town of Sofades in Central Thessaly. The water distribution system is analysed using the software package EPANET 2. It is deduced that using the resilience index, which is related indirectly to system reliability, several scenarios for improving the performance of the system can be assessed.

Key Words: Water distribution system, EPANET, Reliability, Resilience index, Failure index

1. INTRODUCTION

The water distribution system plays a vital role in preserving and providing a desirable life quality to the public. The reliability of supply through the system is a major characteristic of the system. A reliable Water Distribution System (WDS) is able to deliver water to individual consumers in a sufficient quantity and good quality under satisfactory pressure conditions (Al-Zahrani and Syed, 2005).

Reliability of a water distribution system is defined by Kaufmann et al. (1977) as the probability that the system will perform its specified tasks under specified conditions and during a specified period of time. Many researchers (e.g. Goulter 1995; Cullinane et al. 1995) defined reliability of the water distribution system as the ability of the system to meet the demands that are placed on it. Concentrating on the quantity issues, only the demands are specified in terms of the flow to be supplied and the range of pressures at which these flow rates are provided (Yannopoulos and Spiliotis, 2011).

It is interesting to note that there are no universally accepted definitions for the concept of reliability related to water distribution systems. This has resulted into a large number of publications describing these terms by different approaches (Shinstine et al., 2002).

In this study a resilience index is used as the tool for describing indirectly the reliability of the system by employing simple algebraic operations and avoiding complex statistical techniques. Today this resilience index, proposed by Todini (2000), is widely used as a reliability measure, which is a measure of the capability of the network to cope with failures and therefore it is related indirectly to system reliability (Baños et al., 2011).

The assumption of uniformly distributed demand along the pipes is an assumption used when there is poor knowledge about the actual connections and demands (Tsakiris and Spiliotis, 2012). Furthermore the assumption of the nodal demand, although not realistic, it serves to facilitating the analysis of the network. Based on these facts it is obvious that the calculation of power dissipated through the pipes follows also a conventional but not realistic assumption.

Water distribution systems are commonly designed to deliver water at each node, satisfying the demand in terms of the design flow and head. However, in case of demand changes or in case of a pipe failure, the water flow will change and the original network is transformed into a new one with higher internal energy losses. This may make it impossible to deliver the desired flow rate at a minimum acceptable delivery pressure. Providing more power than that required at each node could be one of the options to overcome this problem. This will add sufficient surplus energy to be dissipated internally in case of failures. This surplus has been used by Todini (2000) to characterise the resilience of the looped distribution networks, without involving statistical considerations on actual failures. Needless to say that this increase in energy will lead to improved network reliability (Farmani et al., 2006).

2. RESILIENCE AND FAILURE

The resilience index introduced by Todini (2000) is strongly related to the intrinsic capability of the system to overcome failures while still satisfying demands and pressures at the nodes. From the review of the available literature this index is gaining wide acceptability for evaluating the reliability of urban water distributions systems during the last few years (Farmani et al. 2005a; Reca et al. 2008b).

The concept of resilience has arisen from the property of a material to absorb energy when it is deformed elastically and then, upon unloading to have this energy recovered. In other words, it is the maximum energy per unit volume that can be elastically stored.

Several authors applied the concept of resilience in the field of water resources management. Many authors proposed the term "Resiliency" describing how quickly a water system recovers from a failure once failure has occurred (e.g. ASCE 1998). Therefore, resiliency is basically a measure of the duration of an unsatisfactory condition.

It is a very common assumption to adopt the approach of steady flow conditions in the analysis of urban water distribution systems. Therefore the resilience applied in an urban water distribution system is based on the steady flow analysis. Thus it is strongly related with the power dissipated through the pipes while it actually indicates a measure of the surplus power which is available in the hydraulic distribution system.

For a short description of the method adopted in this paper, the first quantity which is needed is the total available power at the entrance of the water distribution network (P_{tot}). Let also the symbols Q_k and H_k be the flow and the head, respectively, corresponding to each reservoir k, while n_k is the number of reservoirs. The following equation may be written:

$$P_{tot} = \gamma \sum_{k=1}^{n_k} Q_k H_k \tag{1}$$

in which γ is the specific weight of water.

This total available power is split into two types of power as follows:

$$P_{tot} = P_{int} + P_{ext} \tag{2}$$

in which P_{int} is the power dissipated in the pipes and P_{ext} is the power delivered to the users which is related to nodal flow and head:

$$P_{\text{ext}} = \gamma \sum_{\text{i}=1}^{n_n} q_i h_i \tag{3}$$

Very often in the network distribution analysis we suppose that the flow at the nodes is satisfied while we examine the pressure constraints at the nodes (Tsakiris and Spiliotis, 2012). Therefore we can calculate the power dissipated through the pipes (P^*_{int}), provided that the design flow (q^*) is realised, as follows:

$$P_{\text{int}}^{*} = P_{\text{tot}} - \gamma \sum_{i=1}^{n_{\text{n}}} q_i^{*} h_i , \tag{4}$$

From the above analysis it is deduced that the smaller the P^{*}_{int} the better the resilience index.

Finally, Todini (2000) proposed a normalization of the resilience index as follows:

$$I_{\text{r}} = 1 - \frac{P_{\text{int}}^{*}}{P_{\text{max}}^{*}} \tag{5}$$

in which:

$$P_{\text{max}}^{*} = P_{\text{tot}} - \gamma \sum_{i=1}^{n_{\text{n}}} q_i^{*} h_i^{*} \tag{6}$$

is the power dissipated through the pipes provided that the minimum requirements for both the pressure and the flow at the nodes are satisfied.

The above equation can be written in the following form after some algebraic transformations:

$$I_{\text{r}} = \frac{\sum_{i=1}^{n_{\text{n}}} q_i^{*} (h_i - h_i^{*})}{\sum_{k=1}^{n_{\text{r}}} Q_k H_k - \sum_{i=1}^{n_{\text{n}}} q_i^{*} h_i^{*}} \tag{7}$$

According to the above normalized factor, the bigger the I_r is, the higher the resilience becomes which means that the relative power dissipated through the pipes is smaller.

Furthermore, in case additional pumps are inserted into the system, then the resilience index is modified as follows:

$$I_{\text{r}} = \frac{\sum_{i=1}^{n_{\text{n}}} q_i^{*} (h_i - h_i^{*})}{\sum_{k=1}^{n_{\text{r}}} Q_k H_k + \sum_{j=1}^{n_{\text{p}}} (P_j / \gamma) - \sum_{i=1}^{n_{\text{n}}} q_i^{*} h_i^{*}} \tag{8}$$

in which P_j is the power offered by the j pump into the system (j = 1(1)n_p).

From the Eqs. 7 and 8 it is obvious that if there is a significant number of with pressure deficient nodes, that is $q_i^{*}(h_i - h_i^{*}) < 0,$ then the reliability index is negative. Therefore the negative values of the resilience index indicate significant operational problems. Needless to say that it is desirable to achieve positive values for the resilience index. As mentioned previously, the resilience index is always smaller than one.

Todini (2000) also proposed a *Failure Index*, which is used to identify infeasibilities during the optimisation process. According to Todini the failure index, I_f, may be written:

$$I_{\text{fi}} = \begin{cases} 0 & \forall i:\ h_i \geq h_i^{*} \\ q_i^{*}(h_i^{*} - h_i) & \forall i:\ h_i < h_i^{*} \end{cases}, \quad \overline{I_f} = \frac{\sum_{i=1}^{n_{\text{n}}} I_{\text{fi}}}{\sum_{i=1}^{n_{\text{n}}} q_i^{*} h_i^{*}}, \tag{9}$$

From the Equation 9 it is obvious that it would be favourable that the failure index takes small values.

The resilience index allows a compensatory operation between the nodes with surplus of power $\left(q_i^{*}(h_i - h_i^{*}) > 0\right)$, and the nodes with deficient power $\left(q_i^{*}(h_i - h_i^{*}) < 0\right)$. On the other hand the failure index focuses only on the lack of power at the nodes. The failure index expresses only the degree of failure in the hydraulic network. The failure index can be characterized as a rather supplementary index to test the reliable operation of the network.

Conclusively the approach proposed by Todini expresses the adequate power (or lack of power), so that a sufficient surplus exists to be dissipated internally in case of failures. This surplus can be used to characterise the resilience of the looped network. Also the failure index focuses on the lack of power at the nodes.

The resilience index can be used both to identify infeasibilities during the optimisation process and to evaluate the level of defective operation of the system.

3. THE CASE STUDY

The proposed methodology was applied to the Sofades town in Central Thessaly (Greece). The town of Sofades is 15 Km far from Karditsa (municipal centre of the region) and 284 Km from Athens. The town has 8000 inhabitants. Its urban water distribution network has one tank while the terrain in the entire area is flat and the network operates with gravity. The network is comprised of 393 pipes and 251 nodes. The equivalent pipe roughness is assumed equal to 0.1 mm. The total area served by the distribution network is 2 km^2.

The analysis of the network was performed using the EPANET 2 package. As known EPANET 2 package is a computer package that performs hydraulic and water quality simulations of water distribution systems for potable water. The package is capable of determining the flow of water in each pipe, the pressure at each node, the flows and heads at each pump, and the water depth in each storage tank. The package is based on the Gradient method (Todini and Pilati, 1988; Rossman 1993). The Gradient method is a popular method for solving looped water systems. Needless to say that several other methods have been developed and used to analyze water distribution systems as the Hardy Cross method, the linear method, the Newton -Raphson method (e.g. Mays, 2000) or the revised h-Newton-Raphson (Spiliotis and Tsakiris, 2011).

Apart from the analysis of the network, the EPANET 2 can provide additional information on water quality parameters and therefore it facilitates the calculation of the concentration of substances throughout the distribution system.

Several scenarios for improving the performance of the system have been investigated through the determination of the resilience index of the system. These scenarios are briefly presented in Table 1.

Table 1: Scenarios examined for the water distribution system of Sofades town

No	Mean daily consumption (L/cap.day)	Peak factor	Changes of pipes	Other Change
1	200	4.5	No	-
2	200	4.5	the pipe connecting the tank and the network was replaced by a pipe with diameter 440.6 mm	-
3	200	4.5	Changes in a set of pipes	-
4	200	4.5	the pipe connecting the tank and the network was replaced by a pipe with diameter 440.6 mm	Add a Tank
5	200	3	the pipe connecting the tank and the network was replaced by a pipe with diameter 440.6 mm	-

Scenario 1 (existing system): do nothing scenario with 200 L per capita per day and total peak factor 4.5

Scenario 2: 200 L per capita per day and total peak factor 4.5 but the pipe connecting the tank and the network was replaced by a pipe with diameter 440.6 mm

Scenario 3: 200 L per capita per day and total peak factor 4.5 together with the replacement of a set of pipes aiming at reducing the flow velocities.

Scenario 4: 200 L per capita per day and total peak factor 4.5 but an additional tank is added at the elevation +126 m and the pipe connecting the tank and the network is replaced by a pipe with diameter 440.6 mm

Scenario 5: 200 L per capita per day and but the maximum outflow of the network was reduced [*(2/3)* Q_h^{max} *(1*st *scenario),* that is the peak factor is considered equal to 3] and the pipe connecting the tank with the network is replaced by a pipe with diameter 440.6 mm

The pressure and the velocity distribution at the nodes and the pipes, respectively, are presented in the following figures for each of the five scenarios examined (Figs. 1, 2, 3, 4, 5).

Unfortunately the designer of the water distribution system of the town of Sofades selected a rather small pressure head requirement at the nodes for lower cost. As a result the pressure head at several nodes is rather not capable for sustaining the design demand.

The results of the analysis of the 5 scenarios, described previously, are presented in Table 2. The negative values of the resilience index in the first scenario indicate the lack of power at the nodes. Also the significant values of failure index indicate that there is a significant number of nodes characterized by the lack of power.

With regard to the network analysed, by replacing the pipe connecting the tank and the distribution network, a significant improvement is achieved (Scenario 2). Moreover the replacement of a set of pipes can also improve all the pressure heads at the nodes (Scenario 3). Unfortunately as can be understood, the replacement of a set of pipes in a new network is not an attractive option.

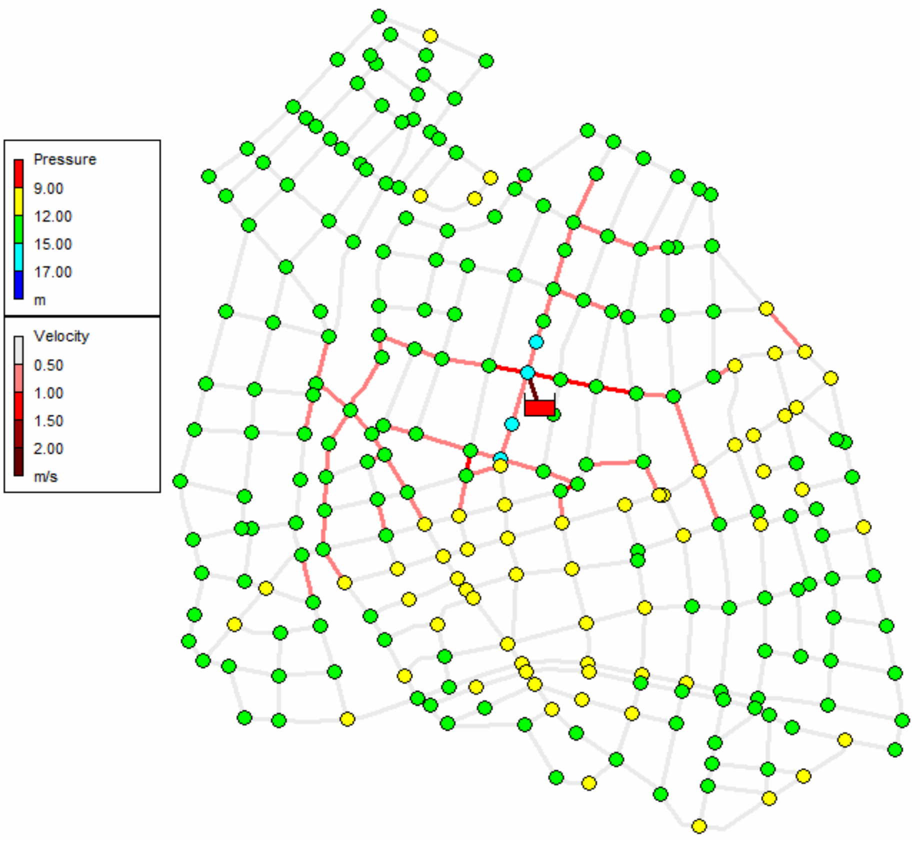

Figure 1: Pressure and velocity distribution of Scenario 1

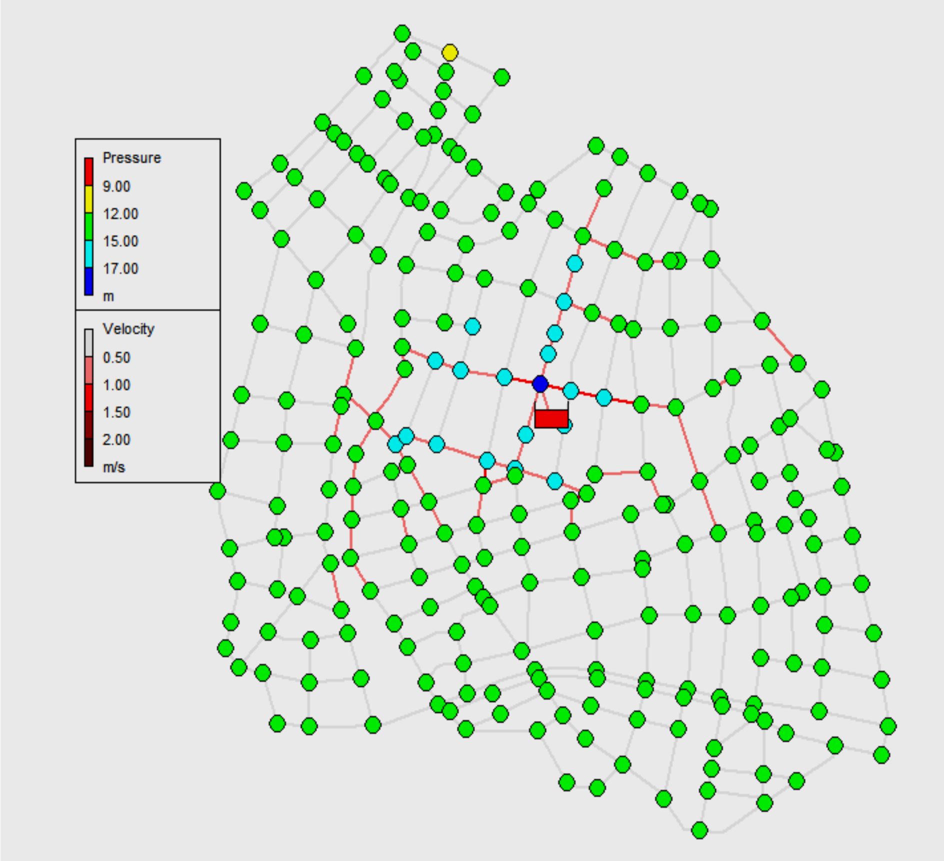

Figure 2: Pressure and velocity distribution of Scenario 2

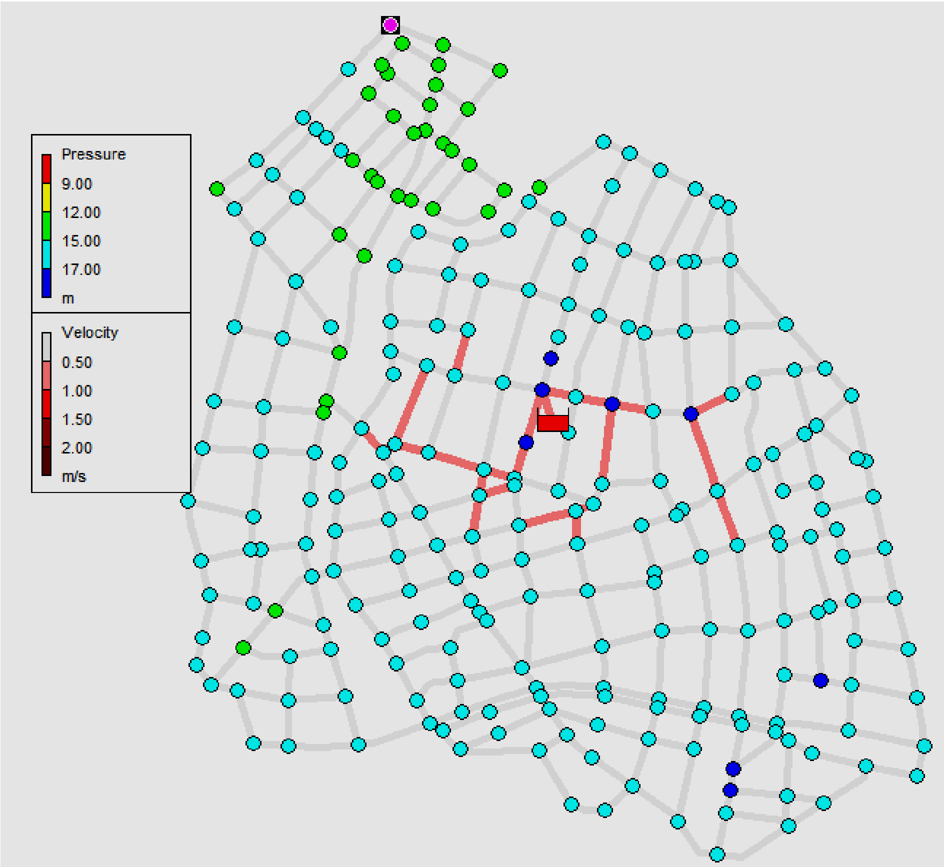

Figure 3: Pressure and velocity distribution of Scenario 3

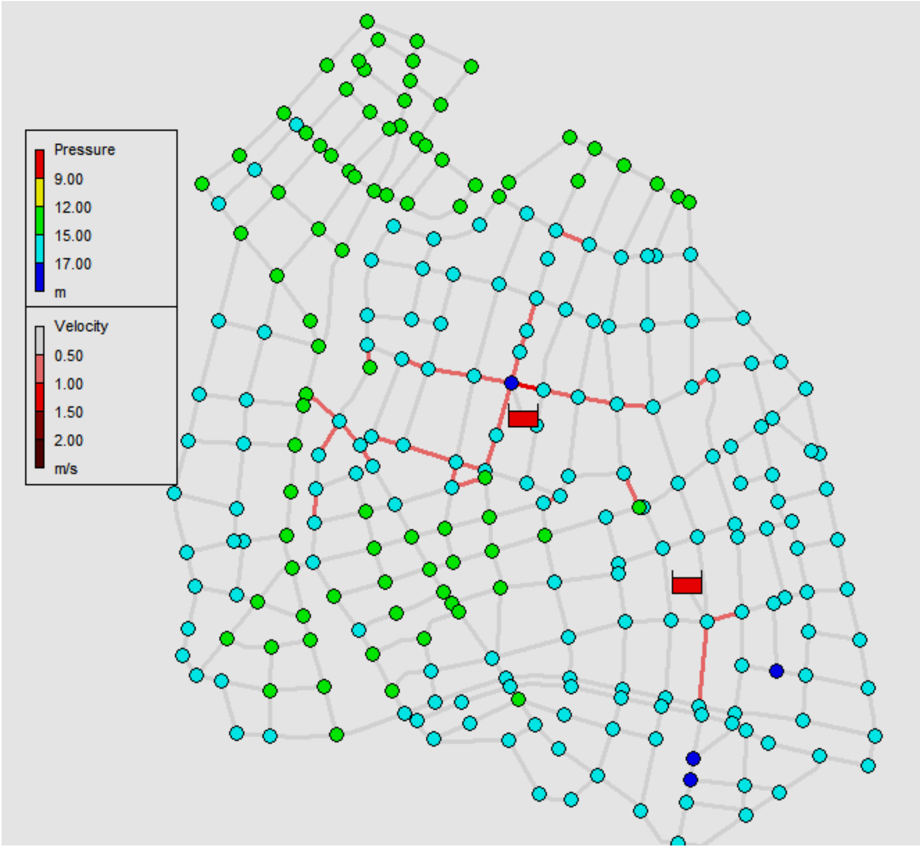

Figure 4: Pressure and velocity distribution of Scenario 4

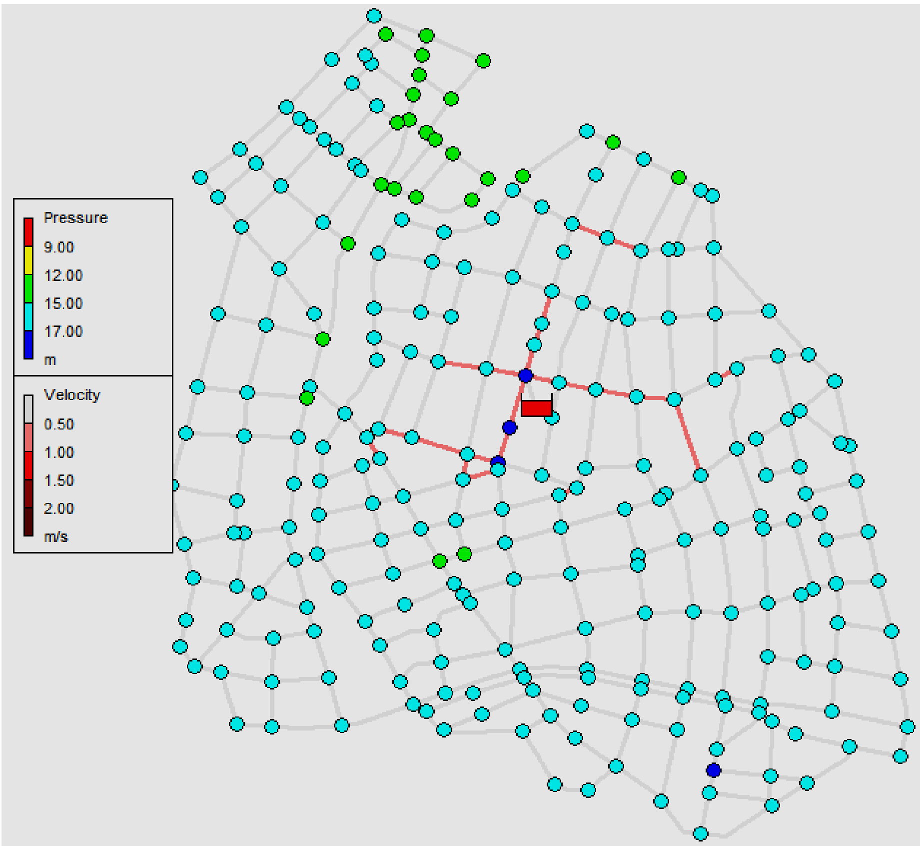

Figure 5: Pressure and velocity distribution of Scenario 5

Further, the incorporation of an additional tank can also improve the pressure head at the nodes of the system. At this point it should be mentioned that the resilience index cannot be used to safely compare the various scenarios since the water source nodes are changed. In this case the denominator of the Eq.7 changes and therefore, the comparisons based on the resilience index cannot produce reliable conclusions.

Obviously the scenario of the reduction of the peak demand (scenario 5) requires a set of measures which should be related with their entire cost of implementation. By following this alternative a significant improvement of the indices can be achieved. This scenario can be seen as an academic exercise rather than a scenario aiming at improving the performance of the hydraulic performance of the existing system. However this scenario indicates that by reducing the demand a significant improvement of the system performance is achieved.

Table 2: The resilience and failure indices applied to the distribution system of the town of Sofades for all 5 Scenarios

Indices	1^{st} (existing) scenario	2^{nd} scenario	3^{rd} scenario	4^{th} scenario	5^{th} scenario
Resilience index I_r	-0.03	-0.02	-0.0016	-0.0054	-0.002
Failure index	0.20	0.14	0.02	0.04	0.02

By comparing the Figures 1-5 and the Table 2 it can be concluded that the resilience index is a quite powerful index for assessing the performance of a system. On the opposite the failure index is a more rigid index since it does not determine all the power dissipated at nodes. It is a rather supplementary index of an intuitional nature without the physical foundation of the resilience index.

Apart from the phase of analysis of the water distribution systems the resilience and failure indices may be applied in optimisation problems of these systems. The problem is formulated as a vector optimisation problem with two objective functions: cost and resilience index (Todini, 2000).

4. CONCLUDING REMARKS

The assessment of reliability of urban water distribution systems is an important task both in the design and operational phases. Among the indirect methods for assessing the reliability of the system are the resilience and the failure index proposed by Todini (2000). The paper adopted this approach to assess the performance of an existing urban water distribution system of a town in Central Thessaly (Greece). Several scenarios for improving the performance of the system were also evaluated through the resilience index and the supplementary failure index. It was concluded that the resilience index can be used for the indirect assessment of the reliability of the system, and that it can provide a useful tool for comparing improvement scenarios.

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