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Models for the assessment of resilience in water distribution networks

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Alla mia famiglia,

A papà Andrea che mi ha insegnato a non mollare mai e a guardare con ottimismo e fiducia la vita

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Abstract

The following thesis work focuses on the use and implementation of advanced models for measuring the resilience of water distribution networks. In particular, the functions implemented in GRA Tool, a software developed by the University of Exeter (UK), and the functions of the Toolkit of Epanet 2.2 were investigated.

The study of the resilience and failure, obtained through GRA Tool and the development of the methodology based on the combined use of EPANET 2.2 and MATLAB software, was tested in a first phase, on a small-sized literature water distribution network, so that the variability of the results could be perceived more clearly and with greater immediacy, and then, on a more complex network, that of Modena. In the specific, it has been decided to go to recreate a mode of failure deferred in time, one proposed by the software GRA Tool, that is failure to the pipes, to make a comparison between the two methodologies.

The analysis of hydraulic efficiency was conducted using a synthetic and global network performance index, i.e., Resilience index, introduced by Todini in the years 2000-2016. In fact, this index, being one of the parameters with which to evaluate the overall state of "hydraulic well-being" of a network, has the advantage of being able to act as a criterion for selecting any improvements to be made on the network itself. Furthermore, during these analyzes, was shown the analytical development undergone over time by the formula of the Resilience Index.

The final intent of this thesis work was to understand by what means to improve the resilience of the system in question, as the introduction of the scenario linked to the rupture of the pipelines was designed to be able to identify the most problematic branches, i.e., those that in the event of a failure it would entail greater damage to the network, including lowering the Resilience Index.

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Introduction

In literature there are several codes, which have been developed with the intent to assess the resilience of water distribution networks: specifically, these codes, using the results of appropriate hydraulic simulations, provide information related to different failure scenarios.

Among these, there is a tool for the Global Resilience Analysis of water distribution systems, called GRA Tool (*Global resilience analysis of water distribution systems*), on which the following thesis work is focused. It is a program that automates simulations, based on the GRA (*Global Resilience Analisys*) algorithm, of a water distribution system and helps to understand the results immediately. Provided the user can supply an Epanet *.inp* file and it contains demand data, the tool can be used to quantify the resilience of a system subjected to potential failure modes.

An interactive results explorer allows the user to easily identify critical system components by service and failure type (e.g., pressure, power or contamination, and failure magnitude or duration).

A network map can be used to color-code components according to their criticality; it is also possible to automatically generate stress-strain response curves and extract key results from them. In fact, the code does not provide a synthetic network index, but rather, depending on the failure scenario considered, returns a list of nodes where the pressure is not satisfied, or the percentage of demand is satisfied compared to that assumed.

The intrinsic resilience of a system is assessed by modeling the failure modes with respect to increasing stress magnitude and estimating the corresponding deformations that occur.

Specifically, within the software, three different failure modes are considered to evaluate the resilience of water networks from different perspectives, namely: pipe failures, excess demand, and substance intrusion.

In the following thesis work has also been analyzed a parallel path that could be used as an alternative to the software GRA Tool, the Epanet Toolkit, based on the combined use of Epanet 2.2 and MATLAB.

The Toolkit consists of a library of functions implemented in MATLAB and designed to allow users to customize the use of hydraulic and water quality simulation software to their application needs. This tool is commonly used for the development of specialized applications, such as optimizing network operation or creating automated calibration models, which require many network analyses to be performed.

The code related to the hydraulic simulation has been used as a base on which to develop a wider MATLAB script, able to quantify the Resilience and Failure Index proposed by Todini (2000). The developed script allows to calculate these Indices in different temporal conditions and with respect to hypothetical scenario of network functioning.

During these analyses, it has been also wanted to show the analytical development undergone in the time by the Resilience and Failure Index formulas, of which in the beginning were proposed a formulation thought for the Demand Driven approach, that subsequently Todini himself has modified, in order to obtain a more advanced form, that is specific for the Pressure Driven modelling approach (*Generalized Resilience and Failure Indices for Use with Pressure-Driven Modeling and Leakage ,2016*).

In a first phase, GRA Tool was used considering one of the failure modes proposed by the software, the pipe failure, applied to a small literature water distribution network, in order that the variability of the results could be perceived more clearly and with greater immediacy, and then it was tested on a more complex literature network, that of Modena. In a second phase, the Resilience and Failure Indices have been calculated on both networks, obtained through the Epanet Toolkit.

At the end of these analyses, the results obtained through GRA Tool, and the Epanet Toolkit were compared to highlight possible criticalities.

1 Simulation models for the study of water distribution networks

1.1 Introduction

As part of the monitoring of water distribution networks, there is a growing need to address issues related to network management. Interventions are aimed at improving reliability and efficiency in existing networks, rather than designing new ones. In the last years, more and more solutions are studied to minimize the failures of the water distribution system and to improve the service to the users through the control of hydraulic parameters. Verification models therefore become an increasingly indispensable tool for evaluating the correct functioning of the system.

The classical models for the hydraulic verification of a water distribution network consider known the topological data and the geometric characteristics of the pipelines, the roughness of the pipelines and the flow rate delivered to the nodes. From the resolution of the system of equations of continuity and of the motion the flow rates circulating in the pipelines and the pressures in the network are determined. The reliability of the result is obviously linked to the correct evaluation both flow rates delivered to the nodes and of the values assumed by the roughness of the pipelines. As far as flow rates are concerned, it is important to schematize the real network functioning considering that they depend also on the available hydraulic load in the nodes.

There are two approaches widely used to solve steady-state hydraulic conditions in a water distribution system, the DDA (Demand-Driven Analysis) and the PDA (Pressure-Driven Analysis).

1.2 Demand-Driven and Pressure-Driven models

In the DDA, nodal demands given by the flow rates delivered to the nodes are always assumed to be satisfied regardless of the available nodal pressure heads. In most cases of hydraulic simulations such as pump operation and nodal head assessment, this assumption of the DDA generally produces accurate results under normal operating conditions. However, the DDA may generate unrealistic results such as negative nodal pressure heads under abnormal hydraulic conditions such as pipe failure, temporal increase in demand and fire. Under such operation conditions, the available demands at some of the demand nodes may be less than the predefined demands since available demand at a demand node is dependent on the available nodal pressure head at that node. Therefore, the actual nodal pressure heads may be negative or unacceptably low when compared to required nodal pressure heads. On the contrary, the nodal demands in the PDA can be fully satisfied only if the nodal pressure head at that node is greater than the required nodal pressure head. Otherwise, nodal demand can be partially satisfied, and it is dependent on available nodal pressure head. For this reason, the unknown nodal demand and nodal pressure head should be solved simultaneously for the PDA simulation of the hydraulic condition. It is why simulation results for abnormal operating condition by the DDA and the PDA are different.

However, it should be noted that they could give us exactly same hydraulic simulation results under the normal operating condition since nodal demands at all nodes can be satisfied when a water distribution network is being operated without a problem. When an event which can paralyze a certain portion of a water distribution system has occurred, it is obvious and reasonable that some of the demand nodes cannot be provided with their full demand and the failure impact area of a water distribution system is dependent on the magnitude and location of the event. The PDA can simulate the demand deficiencies and the affected range of a water distribution system.

Therefore, the PDA is better than the DDA to simulate the hydraulic condition under abnormal operating conditions. Overall comparison between the DDA and the PDA is shown in Table 1.

	DDA (Demand Driven Analysis)	PDA (Pressure Driven Analysis)
Assumptions	Demand of nodes are always fully satisfied	Demands of nodes are dependent on available nodal pressure head
Applications	Normal operation condition	Abnormal operation condition (leakage, failure, pump problem, firefighting demand, etc.)
Reliability for abnormal operating conditions	Low	High
Defects	Negative nodal pressure heads may occur under an abnormal operating condition	Need of a relation equation between nodal pressure heads and nodal flows Solving nodal demand and pressure head simultaneously is very difficult
Solving Method	Iterative procedures to satisfy continuity and equations of motion	Iterative procedure using the DDA simulation

Table 1 *Comparison between DDA and PDA models*

For the correct calculation of the reliability indices, it is necessary to have methodologies capable of evaluating the actual flow delivered in cases where the pressure at one or more nodes is lower than that required to deliver the required flow.

To this end, it should be remembered that almost all the calculation models currently used for the hydraulic verification of the networks have the flow rate Q_j (problem data) delivered in each node (identified with index j), assuming it equal to the required flow rate Q_{rj} and if the hydraulic load H_j (unknown of the problem) is enough to satisfy it.

These models are the DDA, and they give correct results only in the case in which the hydraulic check of the network is positive, or in the case in which, for each node, the hydraulic head is greater than or equal to the H_{rj} value required to satisfy the demand.

If, on the other hand, the calculation highlights the existence of critical nodes for which $H_j < H_{rj}$, the results provided by the model are not correct, since the flow rates Q_j assigned as delivered by the critical nodes are not compatible with the values of the hydraulic head H_j resulting from the calculation.

The conventional approach of the DDA type has so far been considered satisfactory, as the purpose of the hydraulic verification calculation has always been to validate the dimensioning of the network and to detect, in the event of a negative verification, the need for corrective interventions.

In order to evaluate the reliability indices, the need to calculate the effective delivery, even in situations of insufficient pressure, requires a different approach, the PDA, aimed at identifying the solution that satisfies not only the usual equations of motion and continuity, but also the equations $Q_j = f(H_j)$, which in each node relate the flow rate delivered and the hydraulic load available.

To implement the PDA model, it is necessary, therefore, to define a functional link between flow rate and pressure at the nodes and, subsequently, to solve in an iterative way the non-linear system obtained from all the equations that describe the behavior of the network.

The variability of the flow rates delivered to the nodes, generally, is expressed with equations of the type:

$$Q_j = \alpha_j \cdot Q_{rj} \tag{1}$$

where:

- Q_j is the actual flow rate delivered to the node;
- $Q_{rj}$is the required flow rate, i.e., that which should be delivered to the node under sufficient pressure conditions, i.e., the normal operating flow rate;
- α_j is a variable coefficient depending on the hydraulic load.

Considering that, under conditions of sufficient pressure, the flow rate will be equal to the need and that the same will tend to zero at the reduction of the hydraulic load, α_{ji} is quantified as:

$$\alpha_j = 0, if\ H_j \leq H_j^{min} \tag{2}$$

$$\alpha_j = 1, if\ H_j \geq H_{rj} \tag{3}$$

$$0 < \alpha_j < 1, if\ H_j^{min} < H_j < H_{rj} \tag{4}$$

where:

- H_j is the piezometric elevation at the node;
- H_{rj} is the value of the hydraulic load required to satisfy the demand Q_{rj};
- H_j^{min} is the piezometric elevation below which the flow delivered is zero.

For the application of the PDA model it is necessary to define the values of the hydraulic loads H_j^{min} and H_j^{max} and the functional relationship, which allows to determine the coefficient α_j, of which in literature there are different expressions that provide the value as a function of H_j H_j^{min} and H_j^{max}. For the definition of the values of αj according to the (4), they have been proposed in literature different expressions. The most known and used is the one proposed by Wagner et al. (1988), based on the following relationship between the hydraulic load H_j and the flow rate Q_j:

$$H_j = H_j^{min} + K_j Q_j^{\beta} \tag{5}$$

where:

- K_j is a coefficient of hydraulic resistance characteristic of the system fed by the node;
- β is an exponent of hydraulic resistance, generally assumed to be 2, although its value should be calibrated for each node.

The value of K_j can be obtained from the (5) by imposing that $Q_j = Q_{rj}$ for $H_j = H_{rj}$. With this assumption, through simple mathematical steps, it is recognized that:

$$\alpha_j = \left(\frac{H_j - H_j^{min}}{H_{rj} - H_j^{min}}\right)^{\frac{1}{\beta}} for\ H_j^{min} < H_j < H_{rj} \tag{6}$$

1.3 EPANET 2.2

Epanet developed by the EPA (*Environmental Protection Agency*) of the United States of America (https://www.epa.gov/water-research/epanet) is a software application used throughout the world to model water distribution systems. It was developed as a tool for understanding the movement and fate of drinking water constituents within distribution systems and can be used for many different types of applications in distribution systems analysis.

Today, engineers and consultants use this software to design and size new water infrastructure, retrofit existing aging infrastructure, optimize operations of tanks and pumps, reduce energy usage, investigate water quality problems, and prepare for emergencies. It can also be used to model contamination threats and evaluate resilience to security threats or natural disasters.

The software used within the following thesis work for the modeling and hydraulic resolution of the water network is Epanet in the updated version 2.2.

This program allows to execute simulations of networks in pressure with reference both to the hydraulic phenomena and to the quality of the water, in stationary conditions (that is referred to a specific temporal interval) or almost stationary (simulating the behavior of the net subdivided in different temporal intervals in which the conditions can be considered stationary).

It can supply information relative to the flow circulating in every pipe of the network, to the pressure to the nodes, to the level reached from the water in every reservoir, to the concentration of a given substance through the net of distribution during a simulation and to the age of the water circulating inside the system from the moment in which it has been introduced.

Moreover, the code also allows to simulate the presence of the hydraulic devices (such as pumps and valves), to observe the evolution of the main variables of the system in every node or branch of the network, to intervals of prefixed time, on a map and to summarize the obtained results on tables and graphs, furnishing therefore, in synthetic way, a general picture and facilitating the interpretation.

Regarding what has been said it is possible that the software of verification of the networks based on the DDA analysis, among which Epanet, can be used exploiting an approach of PDA type.

In particular, the software Epanet has the possibility, using the *Emitters*, introduced also for the simulation of the water losses, to estimate the flow in exit from the nodes in function of the pressure through an imposed law.

In this case, in addition to the usual equations of motion and continuity, in each node, in which is not verified the condition necessary to perform the DDA analysis, it is introduced a further condition, which provides the relationship between the flow delivered to the node and the actual hydraulic load available. The output flow rate is related to the pressure through the following relationship:

$$Q = C \cdot (H - z)^{\gamma} \tag{7}$$

where:

- Q is the flow rate delivered;
- γ is the exponent which, in the absence of other indications, may be taken as 0.5;
- C is the outflow coefficient.

If $Q_j = Q_{rj}$ when $H_j - z_j = H_{rj} - z_j$, we get:

$$C_j = \frac{Q_{rj}}{(H_{rj} - z_j)^{\gamma}} \tag{8}$$

which, substituted in (7), leads to the following relationship:

$$Q_j = Q_{rj} \cdot \left(\frac{H_j - z_j}{H_{rj} - z_j} \right)^{\gamma} \tag{9}$$

The (9) gives the flow rate delivered to the node as a fraction of the required flow rate, expressed as a function of the pressure deficit with respect to the required operating value; it has a structure like that of (6), with which it coincides if in (6) we assume $H_j^{min} = z_j$ and $\beta = \frac{1}{\gamma}$.

The possibility offered by EPANET 2.2 to simulate the hydraulic functioning of a network by also inserting the *Emitters*, allows to carry out the hydraulic verification according to the PDA approach, with an approximate procedure consisting in the following steps:

1. The network is verified with a conventional calculation of DDA type, imposing that the demand is completely satisfied in all nodes and calculating the consequent hydraulic loads.
2. In all the nodes for which, at the previous step, it results $H_j < H_{rj}$ we put equal to zero the flow rate assigned in exit, and we position an Emitter, with a coefficient C_j calculated with the (8).
3. We verify the system so modified and on the base of the flow rates Q_{ej} given by the Emitters we define the flow rates given to the nodes with the following rules:

$$if\ 0 < Q_{ej} < Q_{rj}, \qquad Q_j = Q_{ej}$$

$$if\ Q_{ej} > Q_{rj}, \qquad Q_j = Q_{rj}$$

$$if\ Q_{ej} < 0, \qquad Q_j = 0$$

Since the second calculation, that simulates the network with the insertion of the *Emitters*, is characterized by lower circulating capacities and by consequent lower losses of hydraulic load in comparison to the first calculation, the nodes that result not critical in the first calculation remain such also in the second one.

The results of the procedure are, therefore, correct and congruent with all the imposed equations, except in the case in which the outgoing flow rates from the *Emitters* must be corrected, as they are greater than the required flow rate or less than zero. Consequently, the degree of approximation of the result depends also on the entity of these corrections.

Wanting to eliminate this error, it is possible to iterate the above procedure by repeating the verification calculation, after eliminating the Emitters in the nodes where the flow rates have been corrected as greater than the required flow rate or less than zero and after assigning the correct values to the flow rates delivered in these nodes ($Q_j = Q_{rj}\ or\ Q_j = 0$).

2 Indices

Various literature indicators can be used to measure the performance of a hydraulic distribution network. Compared to an acceptable minimum operating level, in every possible operating condition, the operating level can be satisfactory or unsatisfactory, and in this case, we speak generically of failure. The simplest and most intuitive performance indicators are the average and variance of the infrastructure outputs of interest: such as delivered flows, operating pressures, or concentrations of chemical species.

However, these statistical indicators alone are not significant enough. It is therefore preferable to combine indices that clearly and exhaustively describe the real one's conditions, in which the networks are. In this regard, the concept of resilience is a valid index quantitative of the adequacy of the engineering choices made in the design phase of a new work, for management and maintenance or for the rehabilitation of an infrastructure existing plumbing (*Resilienza ed entropia come indici di robustezza delle reti di distribuzione idrica*, by *A. Di Nardo1, R. Greco1, M. Di Natale1 & G.F. Santonastaso*).

In 2000, the resilience and failure indices were introduced as a convenient and compact tool to express respectively water-distribution network (WDN) surplus and deficit in satisfying users 'demand, in terms of delivered power (*Gargano and Pianese 2000; Tanyimboh et al. 2001; Ciaponi 2009; Creaco and Franchini 2012*). In their original formulation (*Todini and Pilati 1988*), the mentioned indices, originally thought as WDN design tools, were developed only considering the demand-driven modeling approach, which would include pumps but not leakage. In this case (*Germanopoulos 1985; Wagner et al. 1988; Reddy and Elango 1989; Gupta and Bhave 1996; Tucciarelli et al. 1999; Tanymboh et al. 2001; Alvisi and Franchini 2006; Giustolisi et al. 2008b*), the formulation of Resilience and Failure Index is extended and presents a generalized expression, more convenient for use when dealing with pressure-driven modeling and capable of including the effect of leakage.

Following the original concept, the generalized indices were developed (*Todini and Pilati 1988*) by calculating the power dissipated in the network as a function of the difference between the total power inserted through source nodes and pumps and the net delivered power, whereas the leakage-related power is considered as a loss similarly to the internally dissipated one. Applications to WDN analysis and design proved that using the new formulation in the presence of leakage and pressure-dependent consumptions yields better description of the delivered power excess, compared to the original demand-driven formulation (*Generalized Resilience and Failure Indices for Use with Pressure-Driven Modeling and Leakage,2016*).

2.1 Resilience Index

From a mathematical point of view, the concept of resilience introduced by Todini is close to the definition of robustness: the proposed index represents, in fact, the ratio between the total residual power, which is not dissipated in the network, and the power available to deliver the design flows q_i^* under the minimum design hydraulic loads, h_i^*. If there are no lifting systems within the network considered, it is possible to calculate the Resilience Index using the following relationship:

$$I_r = \frac{P_{OUT}^{*} - P_{OUT}^{min}}{P_{IN} - P_{OUT}^{min}} = 1 - \frac{P_{int}^{*}}{P_{max}^{*}} = \frac{\sum_{i=1}^{N} q_i^{*} \cdot (h_i - h_i^{*})}{\sum_{k=1}^{N_R} Q_k \cdot H_k - \sum_{i=1}^{N} q_i^{*} \cdot h_i^{*}} \qquad (10)$$

In equation (10), P_{OUT}^{*} represents the power associated with the delivery of the flow rates calculated at the N nodes of the network under the hydraulic load h_i, while P_{OUT}^{min} corresponds to the value assumed by the same parameter, considering that the project demands are delivered under a hydraulic load at the nodes exactly equal to the design one, i.e. h_i^* , finally, P_{IN} is the total power fed into the network associated with the flow rates Q_k supplied by N_R tanks with hydraulic load H_k. The second formulation, equivalent to the first, is explained on the assumption that the following quantity:

$$P_{tot} = \gamma \sum_{k=1}^{N_R} Q_k H_k \qquad (11)$$

Represents the total power available at the entrance to the water distribution network, where γ is the specific weight of the water, Q_k and H_k are respectively the flow rate and the head relative to each tank k, while N_R is always the number of tanks. In addition, the equality must hold that:

$$P_{tot} = P_{int} + P_{ext} \qquad (12)$$

where P_{int} is the power dissipated in the pipes, while $P_{ext} = \gamma \sum_{i=1}^{N} q_i h_i$ is the power that is transmitted to the users, in terms of flow rate q_i and hydraulic load h_i at each node, with N the number of nodes. Based on the terms introduced, the Resilience Index I_r can be expressed in equation (10):

$$I_r = 1 - \frac{P_{int}^{*}}{P_{max}^{*}} = \frac{\sum_{i=1}^{N} q_i^{*} \cdot (h_i - h_i^{*})}{\sum_{k=1}^{N_R} Q_k \cdot H_k - \sum_{i=1}^{N} q_i^{*} \cdot h_i^{*}} \qquad (13)$$

where $P_{int}^{*} = P_{tot} - \gamma \sum_{i=1}^{N} q_i^{*} h_i$ is the amount of power dissipated into the grid to meet the total demand and $P_{max}^{*} = P_{tot} - \gamma \sum_{i=1}^{N} q_i^{*} h_i^{*}$is the maximum power which would be dissipated internally to satisfy the constraints in terms of demand and headroom at the nodes.

The Resilience Index has been thought to be included in the range of values [0,1], if the design conditions are satisfied, it represents the residual amount of power available, that can allow the network to work properly even in stress conditions, such as the breakage of one or more pipes or the occurrence of unexpected peaks of water demand at the nodes. When the design conditions are not able to be satisfied, the Resilience Index can theoretically have negative values.

2.1.1 Generalization of the resilience index for the PDA approach

The Resilience Index I_r described so far was originally defined by Todini (2000) for a Demand Driven modeling approach. Considering the notation introduced by *Enrico Creaco, Marco Franchini and Ezio Todini* in the article *Generalized Resilience and Failure Indices for Use with Pressure-Driven Modeling and Leakage* of 2016, the formulation presented in the previous paragraph can also be rewritten as follows:

$$I_r = \frac{\max\,[d^T(H - H_{des}), 0]}{Q_0^T H_0 + Q_p^T H_p - d^T H_{des}} \tag{14}$$

where Q_0 and H_0 are respectively the vector of flow rates and hydraulic loads referred to *Tanks* and *Reservoirs*, i.e., to the nodes of the network with imposed hydraulic load, Q_p and H_p are the vector of flow rates and hydraulic loads referred to the presence of lifting facilities; the terms d and H represent respectively the water demand and the vector of the hydraulic loads in correspondence of the remaining nodes of the network, of which the hydraulic load is not known in advance.

A first generalization of the resilience index to the case of a pressure-based modeling approach has been proposed by *Saldarriaga* et al. (2010), assuming, however, the presence of water losses and the absence of pumps within the system considered. This resilience index I_{rs} (where *s* is for Saldarriaga) takes the following form:

$$I_{rs} = \frac{(q_{user} + q_{leak})^T (H - H_{des})}{Q_0^T H_0 - (q_{user} + q_{leak})^T H_{des}} \tag{15}$$

As can be seen, in this formulation the vector of water losses is also included in the numerator. The generalization of Todini's Index, as defined in equation (14), applicable to the Pressure Driven case can be expressed in implicit form as:

$$I_r = 1 - \frac{P_{int}^*}{P_{max}^*} \tag{16}$$

where $P^*_{int} = \gamma(Q_0^T H_0 + Q_p^T H_p - q_{user}^T H)$ is the actual amount of power dissipated within the network, through resistances along the pipes and water losses, to satisfy the users. Assuming that $q = q_{user} + q_{leak}$, the quantity $q_{user} = C_{user} d$ corresponds to the vector of flows delivered to users through the withdrawal nodes (C_{user} is the diagonal matrix whose generic element expresses the ratio $\frac{q_{user}}{d}$ for the i-th node), while q_{leak} corresponds to the vector of losses assigned to the nodes. Instead, the denominator term $P^*_{max} = \gamma\left(Q_0^T H_0 + Q_p^T H_p - d^T H\right)$ is the maximum power that would be dissipated in the network, if the theoretical condition for which in all network nodes is satisfied:

$$q_{user} = d \ \ and \ \ H = H_{des} = z + h_{des}$$

Realizing inside the expression (16) the opportune algebraic substitutions, we obtain the Index of resilience of Todini generalized with respect to the Pressure-Driven approach in form explicit form, in which the vector q_{leak} does not appear more to the numerator like instead it happens in the version proposed by *Saldarriaga*:

$$I_r = \frac{q_{user}^T H - d^T H_{des}}{Q_0^T H_0 + Q_p^T H_p - d^T H_{des}} \tag{17}$$

It should be noted that the product $Q_p^T H_p$ considers the pumps, which operate as turbines, or any turbines installed in the network. In the case of pumps operating as turbines and/or turbines, the value of product $Q_p^T H_p$ turns out to be negative, that means that, the device takes energy from the system. Similarly, regarding the tanks, which receive water from the network instead of releasing it, from the product $Q_0^T H_0$ we obtain always negative values.

Network configurations for which $q_{user}^T H < d^T H_{des}$ (condition leading to a negative numerator) are unsatisfied in terms of power supplied to users: in fact, these configurations are characterized by a power deficit, compared to what is required. Since the Resilience Index has the purpose of describing the redundancy of the network system, when dealing with networks of this type, I_r can be considered null.

Considering these observations, the most correct form to express the generalization of the index I_r to the Pressure Driven case is the following:

$$I_r = \frac{\max\left[q_{user}^T H - d^T H_{des}, 0\right]}{Q_0^T H_0 + Q_p^T H_p - d^T H_{des}} \tag{18}$$

It should be noted that the terms q_{user}, H, Q_0, and Q_p must have been specially computed through a simulation in PDA mode.

The "max" function has been inserted to ensure that the value of the resilience index is set equal to 0, in the case of network configurations characterized by a power deficit rather than a power surplus. Without this function, such configurations would determine illogical values of I_r (sometimes even smaller than -1 or larger than 1).

Instead, activating the "max" function, all network configurations that present a power deficit are assigned a value of I_r null (also because the magnitude of the power deficit is correctly described through the failure index I_f).

Conceptually, the resilience index indicates what is the residual power that can be dissipated within the of the network, compared to the maximum power that can be dissipated: when the index becomes negative it loses physical sense, but by inserting the cut off at zero, it is possible to understand in the immediate when inside the network there is no power to dissipate.

Written in this way, the resilience index assumes always values between 0 and 1, for all kind of networks. The maximum value, that is I_r = 1, is obtained for a theoretical configuration of the network without losses and dissipations.

The expressions (14) and (18) of the Resilience Index, the result of the last publication proposed by Todini (*Generalized Resilience and Failure Indices for Use with Pressure-Driven Modeling and Leakage,2016*), are the two formulations that have been implemented inside the MATLAB codes for the assessment of resilience, being the most up-to-date and complete, and which have allowed to differentiate the analyses according to the Demand Driven or Pressure Driven approach, showing their operational peculiarities.

2.2 Failure Index

The failure index I_f originally defined by Todini (2000) through the demand-driven modeling approach take on the following form:

$$I_f = \frac{\min\,[d^T(H - H_{des}), 0]}{d^T H_{des}} \tag{19}$$

In a similar way, as for the resilience index, the failure index originally proposed by Todini (2000) can be generalized through the following relationship:

$$I_f = \frac{\min\,[q_{user}^T H - d^T H_{des}, 0]}{d^T H_{des}} \tag{20}$$

Here, again, the quantities q_{user} and H must be computed through a pressure-driven modeling approach. The function "min" in (20) is useful for getting a value of the failure index I_f equal to 0 in the network configurations that feature a power surplus rather than a power deficit. In fact, these configurations are better described through I_r. Written as in (20), the failure index always takes on values ranging from -1 to 0, for all the kinds of networks. Values equal to 0 are obtained for network with no deficit of power, i.e., those that feature positive values of I_r. Values lower than 0, instead, are obtained for networks with deficit of power, i.e., those that feature a value of $I_r = 0$. The lowest possible value $I_f = -1$ is obtained when $q_{user} = 0$, with 0 being the zero vector, i.e., in a network supplying no water to all its users due to low service pressure conditions.

2.3 Difference between resilience and failure index

The main difference between the generalized resilience and failure indices [(18) and (20)], on the one hand, and the original ones [(14) and (19)], on the other hand, lies in the numerator of the former, where the vector q_{user} of nodal outflows to users appears instead of the vector d of nodal demands. Again, variables H and Q_0 in (18) and (20) are derived through pressure-driven modeling, whereas the corresponding ones in (14) and (19) are obtained through demand-driven modeling. The continuity of I_r and If is shown in Fig. 1, as a function of power $q_{user}^T H$ delivered to the WDN users. As formulated in this work, the indices are nonnegative and nonpositive respectively. Furthermore, either index takes on values different from 0 if and only if the other is equal to 0.

Considering this continuity, a generalized resilience/failure index $GRF = I_r + I_f$ can be used to give indications of the WDN power surplus/deficit. As a result of the definition of I_r and I_f, GRF equals I_r, when the latter is larger than 0. Otherwise, for network configurations under deficient power conditions for which $I_r = 0$, GRF is equal to the failure index I_f, which always takes on nonpositive values. Index GFR can be profitably used in the optimization context, as will be shown hereinafter.

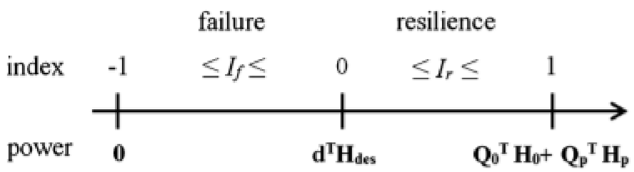


Figure 1 *Range of validity for the resilience and failure indices in terms of values of power delivered to the users (Generalized Resilience and Failure Indices for Use with Pressure-Driven Modeling and Leakage,2016)*

3 GRA TOOL

3.1 Global Resilience Analysis

Resilience can be defined as "the degree to which the system minimizes level of service failure magnitude and duration over its design life when subject to exceptional conditions" (*A tool for global resilience analysis of water distribution systems*).

Extending the concept to a more general definition, resilience refers to the capacity of infrastructure systems, composed of interacting parts that operate together to achieve a target and to be prepared for, and able to respond to, long-term changes of the socio-economic and environmental contexts. Consequently, the concept of resilience must drive the design and management of complex looped WDS.

Evaluation of system performance under identifiable threats is insufficient to obtain a complete picture of a system's resilience, since not all threats that may occur are foreseeable. However, a methodology called *Global Resilience Analysis* (GRA) that utilizes 'stress-strain' type curves and focusses on the response to system failure modes instead of threats, has been developed under the Safe & SuRe project (*A tool for global resilience analysis of water distribution systems*) and demonstrated in urban drainage and water distribution systems. Since system failures are more easily identifiable than threats, and all threats (known or unknown) that result in level of service failure will only do so if they also affect the system, this approach enables a more comprehensive analysis of resilience without the need for knowledge of unknowns.

GRA requires many model evaluations and thus the analysis must be carried out programmatically. However, a lack of automated software for such analyses poses a barrier to wider uptake of the methodology.

Therefore, a simple, user-friendly tool that automates the simulations required for GRA of a water distribution system is used, this software is called GRA Tool, on which the following thesis is focused (*Global resilience analysis of water distribution systems*).

Provided the user can supply an Epanet .inp file for the system and that this contains demand data (an understanding of Epanet and system failure modelling is not necessary), the tool can be used to quantify the resilience of the system to pipe failure, pump failure, demand increase and contaminant intrusion. An interactive results explorer allows the user to easily identify critical system components based on the selected level of service type and failure measure (e.g., pressure, supply or contamination and failure magnitude or duration).

A map of the network can be used to either color-code components based on their criticality in a single component failure analysis or to identify specific combinations of components which result in the greatest level of service failure magnitude or duration when failed simultaneously.

'Stress-strain' type response curves can also be automatically generated, and key findings automatically extracted. Additionally, the tool enables systems to be compared on a like-for-like basis, enabling the effects of proposed interventions on resilience to be quantified and visualized.

As said, GRA Tool utilizes the 'stress-strain' concept where 'stress' represents the system failure magnitude (e.g., number of pipes failed) and 'strain' represents the resultant level of service (e.g., water supply) failure magnitude or duration.

A more resilient system, illustrated by the green line in the figure, is one that results in smaller strain values across a range of stress magnitudes. This approach provides an overview of the response to all possible system failure magnitudes (e.g., from a single pipe failure to simultaneous failure of every pipe in the system), irrespective of their probability, instead of focusing on specific pre-defined scenarios.

3.2 Method

A system's inherent resilience is evaluated by modelling the basic failure modes with increasing stress magnitude and estimating the corresponding strains that arise. The method includes the following steps:

Step 1. Identify the failure mode to be considered (e.g., structural failure, excess demand); this study selects three WDS failure modes, of which details are provided in subsection "Failure modes selected".

Step 2. Identify the system stress associated with the failure mode and the way to simulate it (e.g., WDS simulation with excess load at a node for a specified period);

Step 3. Identify the appropriate system strain and how to measure it (e.g., ratio of unsupplied demand to the total demand required in the strain duration);

Step 4. Simulate failure mode strains under increasing stress magnitude (0% - 100% of maximum stress). Whilst extreme stress magnitudes of up to 100% may be highly improbable, they are theoretically possible and must, therefore, be included if the full range of potential impacts is to be identified. For any given stress magnitude, an appropriate number of failure scenarios is determined. This must be sufficient to reflect important variations in the analysis but cannot include every possibility due to the huge number of possible failure scenarios.

Step 5. Generate a resilience stress-strain curves showing the mean, maximum and minimum strains generated from the simulations for any given stress magnitude.

3.3 Failure modes

Within the software, three different failure modes are considered to assess the resilience of water networks from different perspectives, namely: pipe failures, excess demand and substance intrusion, as can be seen in Figure 2.

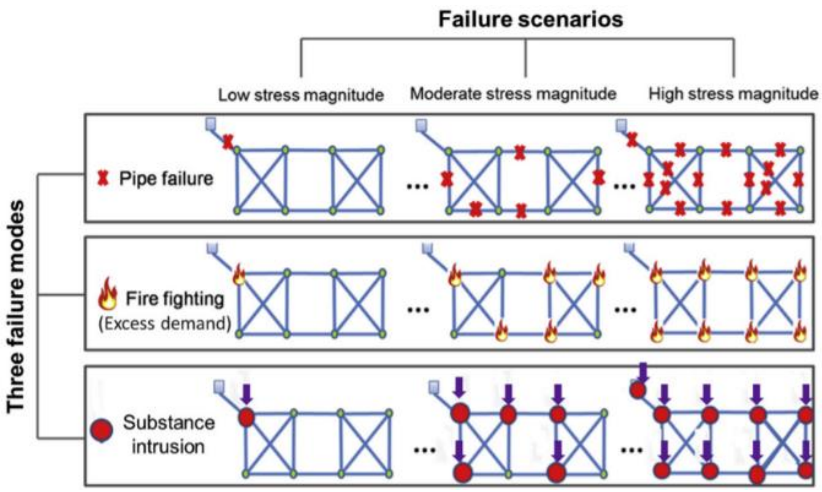


Figure 2 *Schematic of the three failure modes and corresponding failure scenarios. Crosses, flames, and arrows represent the location of pipe failures, increased demands and substance intrusions respectively (Global resilience analysis of water distribution system)*

Responses to systematic pipe failure can reveal the resilience of the system to the loss of physical connectivity (structural). Responses to excess demand indicate resilience to additional point loads without structural failure (functional). Responses to substance intrusion reflect resilience of the system to water quality disturbance without a change of system structure or hydraulic loading.

Hence, WDS resilience is comprehensively evaluated in terms of structure and function. For each case, the specific evaluation method is described. Investigating different failure modes individually helps us to distinguish the systems' dynamic response to specific failures. This is critical before moving to more complicated cases.

Scenario generation, network simulation using Epanet, and calculation of level of service failure magnitude and duration are completed automatically based on the user inputs provided.

For a system failure magnitude of x, pipe failure is modelled by setting x pipe statuses to 'closed' in Epanet at the specified time and for the specified duration. Demand increase is modelled by increasing demand at x nodes by a fixed (user specified) percentage at the specified time and for the specified duration. Contaminant intrusion is modelled by applying a contaminant mass booster (with user specified flow rate) at x nodes at the specified time and for the specified duration.

For each system failure scenario, the following level of service failure (i.e., strain) measures are calculated:

1. Pressure and supply failure durations (duration for which at least one node in the system is subject to pressure / supply failure, based on the user specified pressure requirement);

2. Pressure failure magnitude (total volume of demand subject to unsatisfactory pressure OR maximum instantaneous fraction of demand subject to unsatisfactory pressure during the simulation period);

3. Supply failure magnitude (total volume of demand not supplied OR maximum instantaneous fraction of demand not supplied during the simulation period).

Given that Epanet is a demand-driven model and supply is not directly calculated, supply (S) at each node and time step is estimated:

$$if\ P \leq 0 : S = 0$$

$$if\ 0 < P < P_{lim} : S = D\sqrt{\frac{P}{P_{lim}}}$$

$$if\ P \geq P_{lim} : S = D$$

where P is the modelled pressure and P_{lim} is the user-specified minimum allowable pressure.

When the selected system failure mode is 'Contaminant intrusion', the following additional level of service failure measures are calculated:

4. Contamination duration (duration for which at least one node with demand has an unacceptable contaminant concentration, based on the user specified limit);

5. Contamination magnitude (total volume of supply contaminated OR maximum instantaneous fraction of supply contaminated during the simulation period).

Following completion of the simulations, minimum, mean and maximum values for each level of service failure measure are calculated at each system failure magnitude for use in response curves.

4 Epanet Toolkit

In the following work of the thesis has also been analyzed a parallel path that could be used as an alternative to the software GRA Tool, such tool is the Epanet Toolkit (*US Environmental Protection Agency*), based on the combined use of Epanet 2.2 and MATLAB.

This tool has allowed to calculate the Resilience and Failure Index as tool to measure the performance of a water distribution network: to do this, have been compared the results of different scenarios, obtained simulating the breakage in succession of the pipes of the network, or assuming increases in water demand at the nodes.

This is an open-source software, created to provide a programming interface to the latest version of Epanet using the MATLAB environment, a high-level technical calculation program. Both Epanet and its Toolkit were originally developed by the US Environmental Protection Agency (USEPA).

The Toolkit consists of a library of functions implemented in MATLAB and designed to allow users to customize the use of the hydraulic and water quality simulation software to their application needs.

More than 50 functions are available, which can be exploited for a variety of uses, including: opening network description files; reading and modifying various network design and operational parameters; and running long-term simulations, accessing results as they are generated or saving them to files in a format specified directly by the user.

With the Toolkit, you can also add functionality from integrated modeling environments based on CAD (*Computer Aided Design*), GIS (*Geographic Information System*), and database packages. Because of these features, this tool is commonly used for the development of specialized applications, such as optimizing network operation or creating automated calibration models, which require many network analyses to be performed.

Based on what has been said, the Toolkit is the set of all the mathematical functions, visualizable in explicit form through a corresponding MATLAB script, which correspond to the commands of the Epanet user interface, of which, however, in Epanet only a graphic or tabular restitution is provided.

For what concerns the case study, among all the functions available inside the Toolkit we have concentrated on the one able to realize the hydraulic analysis of the network under examination (*EX2_Hydraulic_analysis.m*): in fact, this function, recreated as a MATLAB code, allows to solve the loaded water network, as Epanet's interface would do, but at the same time the simulation results are provided in matrix form, so that it is more immediate to use them later for the resilience and failure calculation.

The first part of the code consists of two initial commands, whose formulation can be seen in Figure 3:

```
%% Run hydraulic analysis of a network

% Load a network.
d = epanet('Rete di partenza_TLN_PDA.inp');

% Set simulation time duration.
hrs = 23;
d.setTimeSimulationDuration(hrs*3600);
```

***Figure 3** First commands of the solving script*

The first command allows you to recall the .inp file containing the network to be analyzed, while the second allows you to set the hydraulic simulation in *Single Period* mode, i.e., with respect to a single instant in time, or in *Extended Period* mode, i.e., with respect to the duration of an entire day, which in turn for simplicity is divided into hourly intervals.

Subsequently, 5 different hydraulic analysis modes are implemented, which are distinguished from each other based on the type of events considered and based on the speed of resolution of the network, to be considered as an index higher or lower efficiency. These instructions are shown in Figure 4 and 5.

```
%1 Hydraulic analysis using epanet2d.exe binary file.
% (This function ignores events)
tic
hyd_res_1 = d.getBinComputedAllParameters;
time_1 = toc;
tic;
hyd_res_2 = d.getComputedTimeSeries;
time_2 = toc;

%2 Hydraulic analysis using ENepanet binary file (fastest).
% (This function ignores events)
tic;
hyd_res_3 = d.getComputedTimeSeries_ENepanet;
time_3 = toc;
```

***Figure 4** Hydraulic analyses that ignore intermediate events*

```
%3 Hydraulic analysis using the functions ENopenH, ENinit, ENrunH, ENgetnodevalue/&ENgetlinkvalue, ENnextH, ENcloseH.
% (This function contains events)
tic;
hyd_res_2 = d.getComputedHydraulicTimeSeries;
time_4 = toc;

%4 Hydraulic analysis step-by-step using the functions ENopenH, ENinit, ENrunH, ENgetnodevalue/&ENgetlinkvalue, ENnextH, ENcloseH.
% (This function contains events)
tic;
d.openHydraulicAnalysis;
d.initializeHydraulicAnalysis;
tstep=1;P=[];T_H=[];D=[];H=[];F=[];
while (tstep>0)
    t=d.runHydraulicAnalysis;
    P=[P; d.getNodePressure];
    D=[D; d.getNodeActualDemand];
    H=[H; d.getNodeHydaulicHead];
    F=[F; d.getLinkFlows];
    T_H=[T_H; t];
    tstep=d.nextHydraulicAnalysisStep;
end
d.closeHydraulicAnalysis;
time_5 = toc;
```

Figure 5 *Hydraulic analyses that consider intermediate events*

It should be noted that, for the purposes of the final calculation code, only the hydraulic analyzes which do not report the eventual results between the output results (i.e., *hyd_res_2* and *hyd_res_3*) are considered, i.e., those which do not take into account the intermediate time instants, formed, for example, in the moment of attack o detachment of the pumps o in the moment of emptying a tank. In this specific case, we have chosen to consider only the *hyd_res_2* hydraulic analysis.

The second part of the resolving code was created specifically from scratch, to obtain the necessary elaborations for the analysis of the case study. In this section, in fact, to show the evolution of the formula proposed by Todini, passing from the DDA case to the PDA case, the updated formulations of the Resilience and Failure Indices, presented in the scientific article *Generalized Resilience and Failure Indices for Use with Pressure-Driven Modeling and Leakage*" (2016) by *Enrico Creaco, Marco Franchini, Ezio Todini*, already commented in the previous paragraph, have been implemented in different scripts.

In Figure 6 are summarized the lines of code for the calculation of the Resilience and Failure Indices.

```
%% Calculation of the Todini Resilience Index in 24h
reservoir=1;
tank=0;
n=reservoir+tank;
dimD=size(hyd_res_2.Demand);
ncol=dimD(1,2); %consider the total number of columns of the matrix D
ndef=ncol-n;  %subtract the columns related to tanks and reservoirs

% Creation of terms to use in formulas
q=[hyd_res_2.Demand(:,1:ndef)]; %to be understood as quser
h=[hyd_res_2.Head(:,1:ndef)];
E=[d.getNodeElevations];  costante= 1.5+5+30; hdes=costante+E(:,1:ndef);
Q0=-1*[hyd_res_2.Demand(:,ndef+1:ncol)];
H0=[hyd_res_2.Head(:,ndef+1:ncol)];

dtable=readtable('q.txt');
dtableq=table2array(dtable); %to be understood as d
dtable=readtable('quser.txt');
tablequser=table2array(dtable); %to be understood as quser

%Implementation of the formulas:
%IR=[(q.*h)-(d.*hdes)]/[(Q0.*H0)-(d.*hdes)]
%IF=[(q.*h)-(d.*hdes)]/(d.*hdes)]
a=(q.*h)-(dtableq.*hdes);
b=(Q0.*H0);
c=(dtableq.*hdes);

IR=max(0,sum(a,2))./[sum(b,2)-sum(c,2)];
IF=min(0,sum(a,2))./sum(c,2);
```

***Figure 6** implementation of Resilience and Failure indices*

In addition, a minus sign has been inserted in correspondence of the term Q_0 to make the convention regarding the entry and exit of water from Reservoir between Epanet and MATLAB coincide. The minus sign is related to the fact that, when a flow enters the network and leaves the tanks, you are feeding dissipate power: for Todini formulation, the water entering the network corresponds to an input power, while Epanet assumes negative the water leaving the single tank and entering the network. Therefore, putting a minus sign in front of the results provided by Epanet, we obtain a power to be considered positive, as it is entering the network.

Depending on the study scenario considered, the above instructions were then inserted into appropriate *for-loops*, created to simulate different conditions of analysis.

Finally, the script concludes with some lines of command necessary to allow the restitution in graphical form of the numerical values obtained. Passing from a simulation to the other, these instructions can change according to the variables inserted in the axes of the graphs.

5 Case studies

5.1 Introduction

The study of the Resilience and Failure Index, obtained through GRA Tool and the development of the methodology based on the combined use of EPANET 2.2 and MATLAB software, it was tested in a first phase, on a small-sized literature water distribution network, so that the variability of the results could be perceived more clearly and with greater immediacy.

In the specific, it has been decided to go to recreate a mode of failure deferred in time, one proposed by the software GRA Tool, that is failure to the pipes, to make a comparison between the two methodologies.

The goal, subsequently, is to apply GRA Tool and the Toolkit on a more complex network, that of Modena.

Therefore, the first step was to use GRA Tool by simulating the individual breakage of the pipes, on both networks, first on the simpler network and then on the more complex one of Modena, and finally the elaborations of this software were analyzed.

Then, after having managed to configure the various MATLAB scripts in such a way as to be able to calculate the Resilience and Failure index, it was decided to obtain the values in different operating modes, to be able to compare the results.

In a first time, the code has been made to work fixing, through the command *Set simulation time duration*, two different temporal settings: the first one related to the *Single Period* mode, which has provided a single value of Resilience and Failure Index referred to a certain instant of time, the second one related to the *Extended Period* mode, which has allowed to obtain the variation curve of the Resilience and Failure Index of the network during the day.

Subsequently, maintaining unchanged the setting on the *Extended Period*, the attention has been focused on highlighting the peculiarities of the two approaches of hydraulic simulation, that the version of EPANET2.2 puts to use, that is the modality DDA and PDA, being able, therefore, to exploit the double formulation of the Resilience and Failure Index proposed by Todini for each of the two approaches (*Generalized Resilience and Failure Indices for Use with Pressure-Driven Modeling and Leakage,2016*).

The basic script, left in PDA mode, has been then implemented with special instructions, that would allow to continue to calculate the Resilience and Failure Index of the network, but within one simulation scenario, the failure to the pipes.

Knowledge of hydraulic resilience can be used as a measure of the ability of a water distribution network to provide a minimum level of service under certain operational and failure conditions.

In fact, resilience reflects the adaptive capacity time adaptation of a network, both following short-term events, such as the breakage of one or more pipelines.

The introduction of the scenario linked to the breakage of the pipelines has been thought to be able to individuate the most problematic branches, that is those that in case of failure would involve greater damages to the net, among which the lowering of the Resilience Index.

In this regard, this analysis can be very useful in the case in which a plan of substitution of the pipelines is being planned or if it is necessary to verify their integrity, in how much it allows to understand on which pipelines to place greater attention.

5.2 Synthetic case study

5.2.1 Description

The hydraulic scheme of the synthetic network and its topological description are shown below:

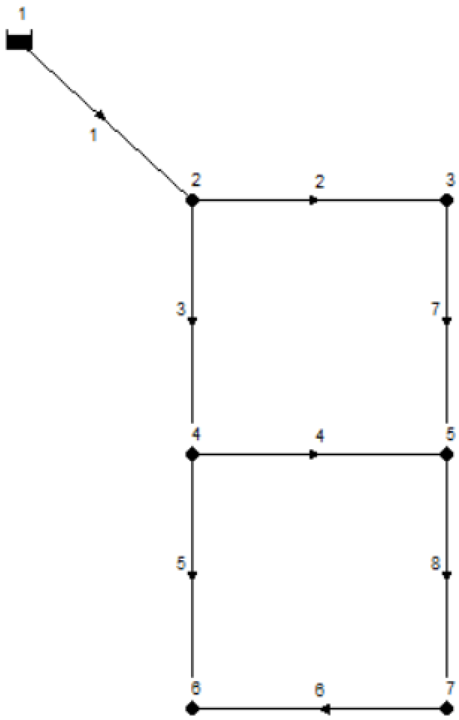


Figure 7 *Synthetic network*

This is a theoretical water distribution network, whose model has been reproduced in Epanet with data related to the direct layout and water consumption already assigned to both pipelines and nodes. This first case study is the simple network of Alperovits and Shamir (1977) (*Generalized Resilience and Failure Indices for Use with Pressure-Driven Modeling and Leakage*) made up of 6 nodes and 8 pipes (Figure 7). The choice of such a simple network as first case study is motivated by the necessity of facilitating the analysis of the results.

As far as the network layout is concerned, this is fed by a single-entry point, that is Reservoir R_1, whose hydraulic load is equal to 210 m. To each node of the network are associated: the elevation quota, the average annual demand, and the law of variation of water demand, which has been assigned equal to the whole network.

The network was analyzed in a snapshot scenario representative of the peak demand and the Hazen Williams roughness coefficient equal to 130 $m^{0.37}$ s^{-1} was used for all network pipes.

Values of h_{min} and h_{des} equal to 0 and 30 m respectively were considered for the calculations and the network configuration with uniform pipe diameters is equal to 457.2 mm.

To every pipeline of the net are attributed: a diameter, a length, and a roughness. It is specified that inside the model there are no pumps or valves. The main geometric and hydraulic characteristics of pipelines and nodes are summarized in Tables 2 and 3.

Network Table - Links

Link ID	Length m	Diameter mm	Roughness
Pipe 1	1000	457.2	130
Pipe 2	1000	457.2	130
Pipe 3	1000	457.2	130
Pipe 4	1000	457.2	130
Pipe 5	1000	457.2	130
Pipe 6	1000	457.2	130
Pipe 7	1000	457.2	130
Pipe 8	1000	457.2	130

***Table 2** Network pipeline properties*

Network Table - Nodes

Node ID	Elevation m	Base Demand LPS
Junc 2	150	27.7
Junc 3	160	27.7
Junc 4	155	33.3
Junc 5	150	75
Junc 6	165	91.6
Junc 7	160	55.5
Resvr 1	210	#N/A

***Table 3** Network node properties*

The Base Demand (Figure 8), that is the average annual water consumption of the network users, is an input data, that is it has already been assigned to each node of the model, and it has been assumed constant, this means that the consumption of users in the 24 h is constant.

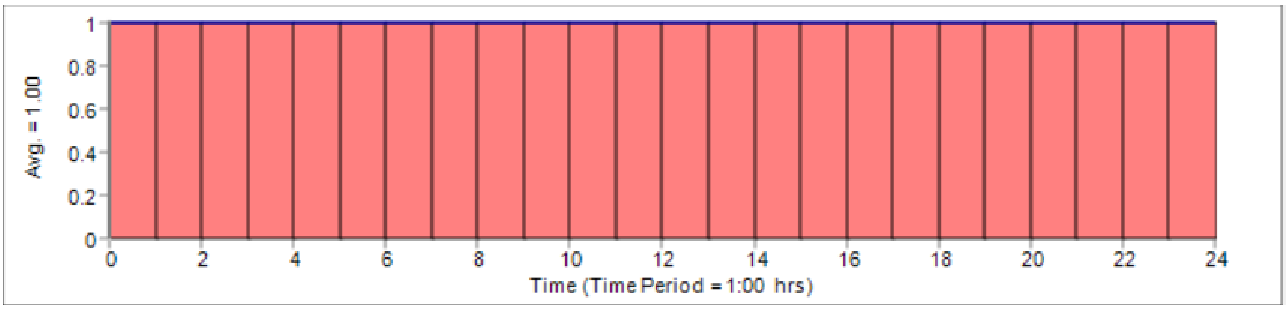


***Figure 8** Base Demand trend in 24 hours*

5.2.2 GRA Tool results

Upon launching, the tool provides options to run a new analysis, load results for a single system or load results for a comparison. Running a new analysis requires multiple user inputs, which are detailed afterwards. Following the analysis, results are presented in the single system results explorer and saved for later reference.

All results shown when illustrating the outputs of the tool are for the synthetic water distribution system considered, which contains 8 pipes and 6 nodes.

User inputs required and available options for the analysis include:

1) Analysis type ('Individual failures only', 'Partial GRA' or 'Full GRA')

2) Simulation duration (in this case 24 hours)

Selecting 'Individual failures only' provides an analysis in which the effects of any single system component failure on level of service provision is evaluated. This is not a GRA as it considers only one system failure magnitude; however, it provides very quick results and may be used to obtain a preliminary indication of critical components.

'Partial GRA' considers system failure magnitudes from zero to a user specified maximum (e.g., up to 10 simultaneous pipe failures); this is faster than a full GRA and can be used to restrict the analysis to smaller / more probable system failure magnitudes.

'Full GRA' provides a comprehensive resilience analysis in which all system failure magnitudes, from 0% to 100%, are evaluated.

In this case the *Individual failure only* and a simulation duration equal to 2 hours are considered, as could be seen in the Figure 9.

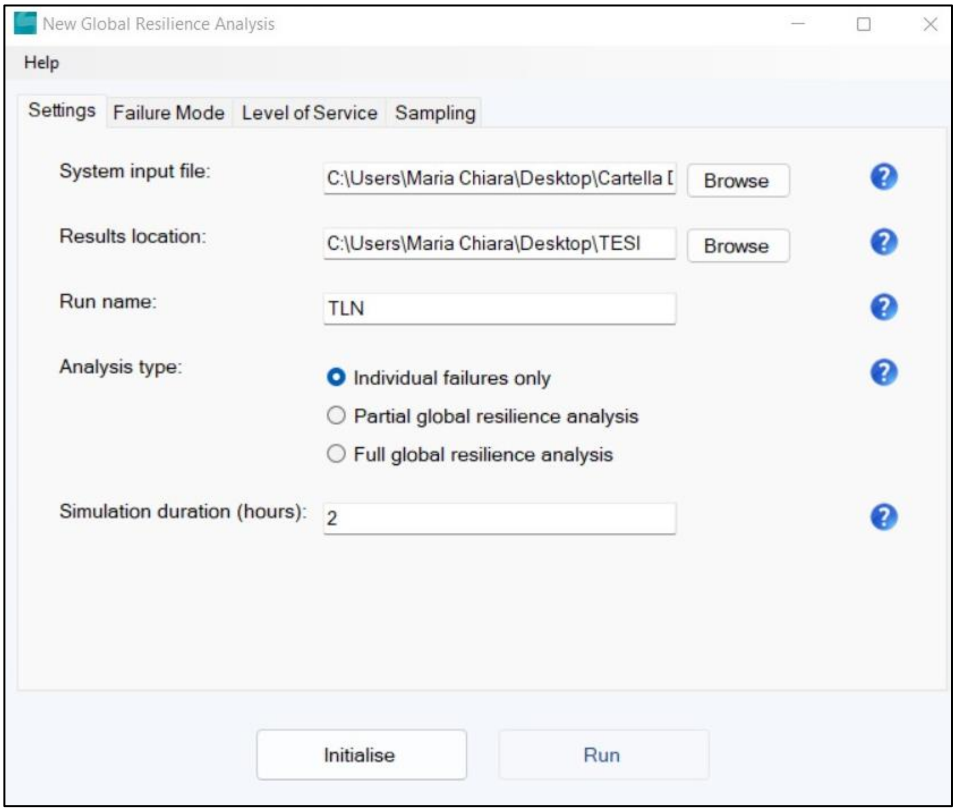


Figure 9 *Settings options*

3) Stress characteristics:

a. System failure mode ('Pipe failure', 'Pump failure', 'Demand increase' or 'Contaminant intrusion')

b. Maximum system failure magnitude (only required if the analysis type selected is 'Partial GRA')

c. System failure start time and duration

d. Demand increase (only required if the selected system failure mode is 'Demand increase')

e. Contaminant mass booster flow rate, if applicable (only required if the selected system failure mode is 'Contaminant intrusion')

The failure of the system chosen for the following study is the *pipe failure*, this breakdown was simulated starting from the first hour, with a duration of 1 hour (Figure 10).

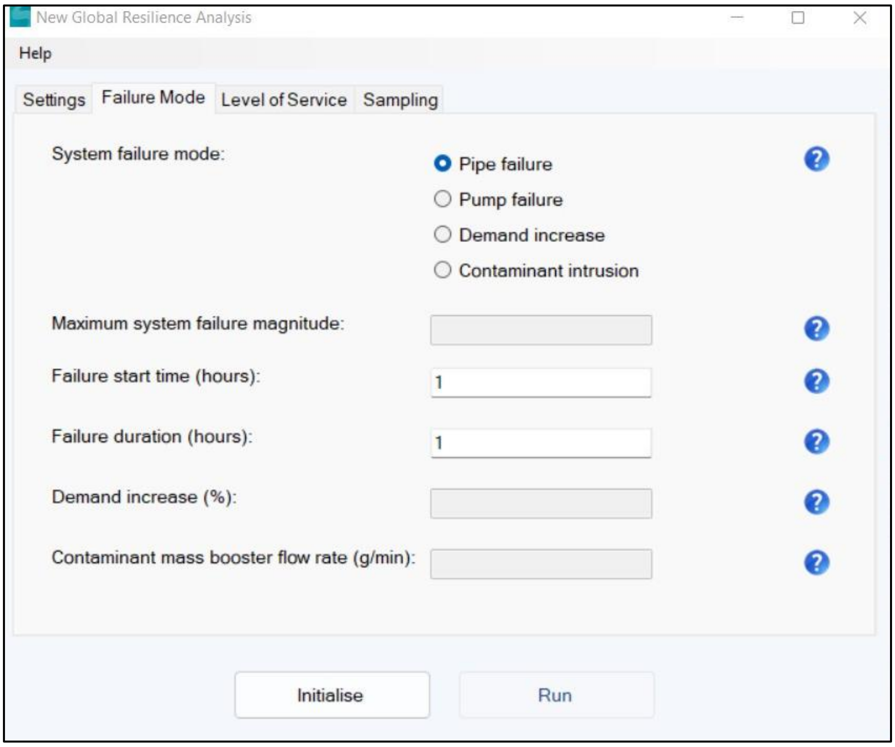


***Figure 10** Failure mode options*

4) Strain specification:

a. Minimum allowable pressure

b. Maximum allowable contaminant concentration (only required if the selected system failure mode is 'Contaminant intrusion')

5) Parameters for random sampling:

Number of random samples for each system failure magnitude and seed options for random sample generation; not required if the analysis type selected is 'Individual failures only'.

Results shown when presenting the *Results Explorer* are for analyses with a simulation duration of 2 hours, system failure duration of 1 hours and system failure start time of 01:00 on day 1. The system failure modes evaluated are pipe failure and the minimum allowable pressure equal to 30 m.

System failure mode: PIPE FAILURE

Scenario generation, network simulation using Epanet, and calculation of level of service failure magnitude and duration are completed automatically based on the user inputs provided. For a system failure magnitude of *x*, pipe failure is modelled by setting *x* pipe statuses to *closed* in Epanet at the specified time and for the specified duration.

For the system failure scenario, the following level of service failure (i.e., strain) measures are calculated:

1. Pressure and supply failure durations
2. Pressure failure magnitude
3. Supply failure magnitude

The measure of system failure magnitude could be express both in terms of number of pipes failed and in percentage of pipes failed, in this case, equal to 12,5 %. Given that Epanet is a demand-driven model and supply is not directly calculated, supply (S) at each node and time step is estimated using the following equation:

$$if\ P \leq 0 :\ S = 0$$
$$if\ 0 < P < P_{lim} :\ S = D\sqrt{\frac{P}{P_{lim}}}$$
$$if\ P \geq P_{lim} :\ S = D$$

Where *P* is the modelled pressure and P_{lim} is the user-specified minimum allowable pressure.

As will be seen below, the software generates a network map that can be used to color-code components based on their criticality in a single component failure analysis. Specifically, four criticality bands are automatically created, called *critically*, represented in four different colors (red, orange, yellow and green).

These criticalities cannot be modified by the user but are generated as output by the software: is taken the minimum value of failure, in which no pipe breakage occurs (*No system failure*) and the maximum value of failure (worst combination), and in this way is created the failure range, which is always divided into four and depending on the value for each scenario, is attributed a *critically* from 1 to 4. So, this coloring means that the pipes do not have the attribute of the failure quantity that they determine, but they have the attribute of the criticality with which they have been classified.

Pressure failure durations (hours) is the duration for which at least one node in the system is subject to pressure failure, based on the user specified pressure requirement, in this case 30 m (Figure 11).

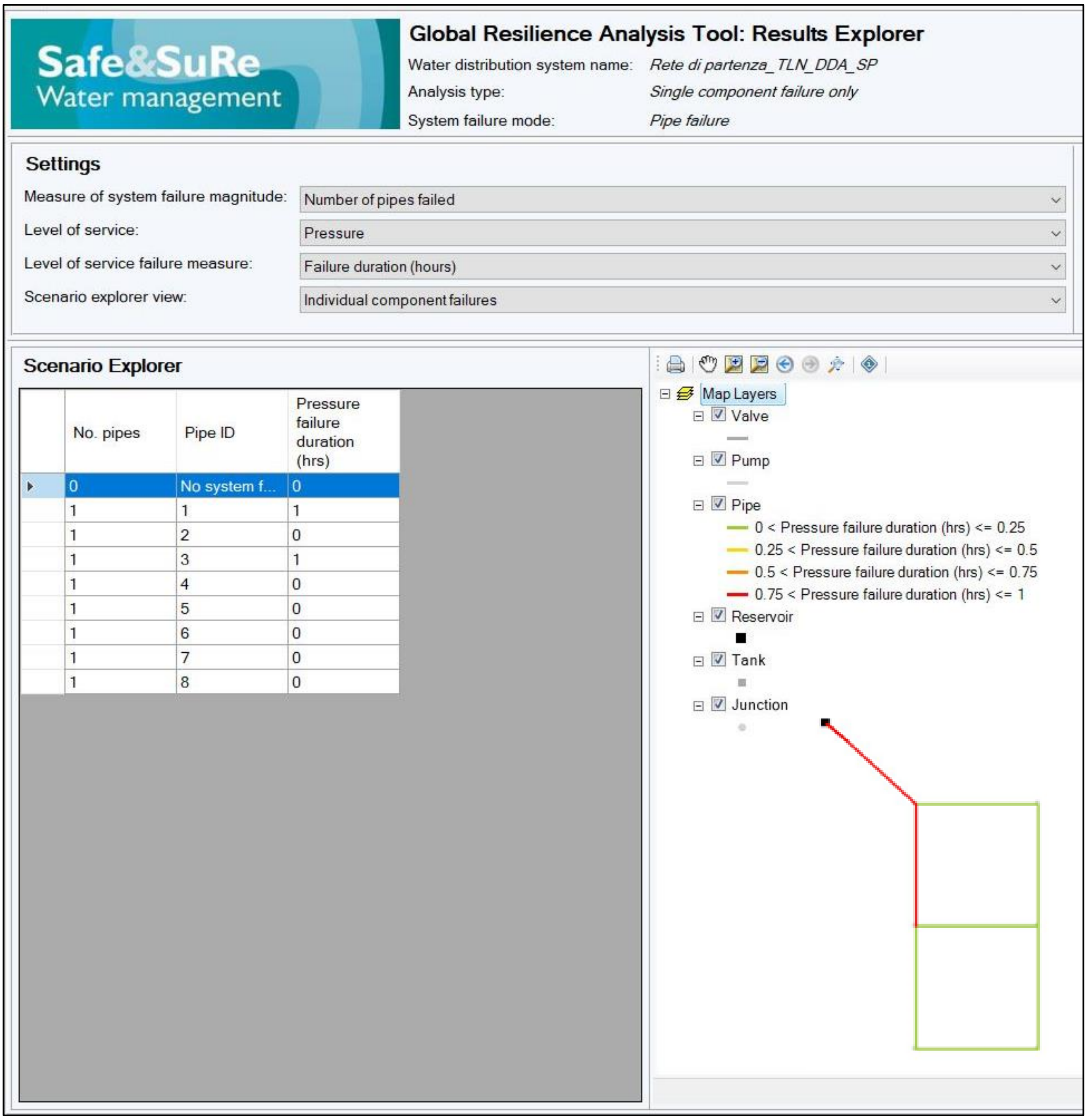


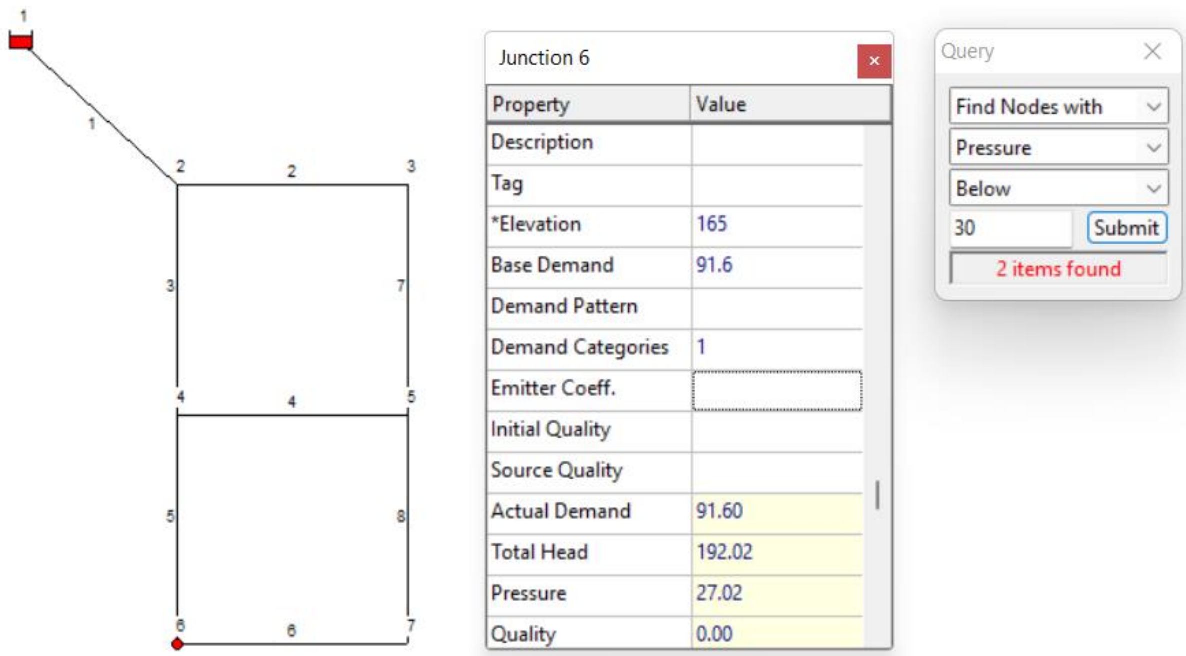
Figure 11 Pressure failure duration (hours)

Pressure failure magnitude can be expressed in liters (Figure 12) or in fraction (Figure 13): in the first case is the total volume of demand subject to unsatisfactory pressure, in the second case is the maximum instantaneous fraction of demand subject to unsatisfactory pressure during the simulation period.

To understand where these results come from, the procedure adopted is reported below. As said before, for a system failure magnitude of x, pipe failure is modelled by setting x pipe statuses to *closed* in Epanet at the specified time and for the specified duration. For a better understanding of the procedure, it has been simulated the breakup of the **Pipe 3**.

The steps to follow to obtain the values of *Pressure failure magnitude (liters)* are listed below:

1. Close Pipe 3 and click *Run*
2. Check which node has the Actual Demand not satisfied (with pressure less than 30 m), in this case the Junction 6.
3. Convert l/s in Ml/h



$$Actual\ Demand_{J6}\ (l/s) \cdot\ 3600\ \cdot 10^{-6} = 91.60\ \cdot 3600\ \cdot 10^{-6} = \mathbf{0.32976}\ \frac{\boldsymbol{Ml}}{\boldsymbol{h}}$$

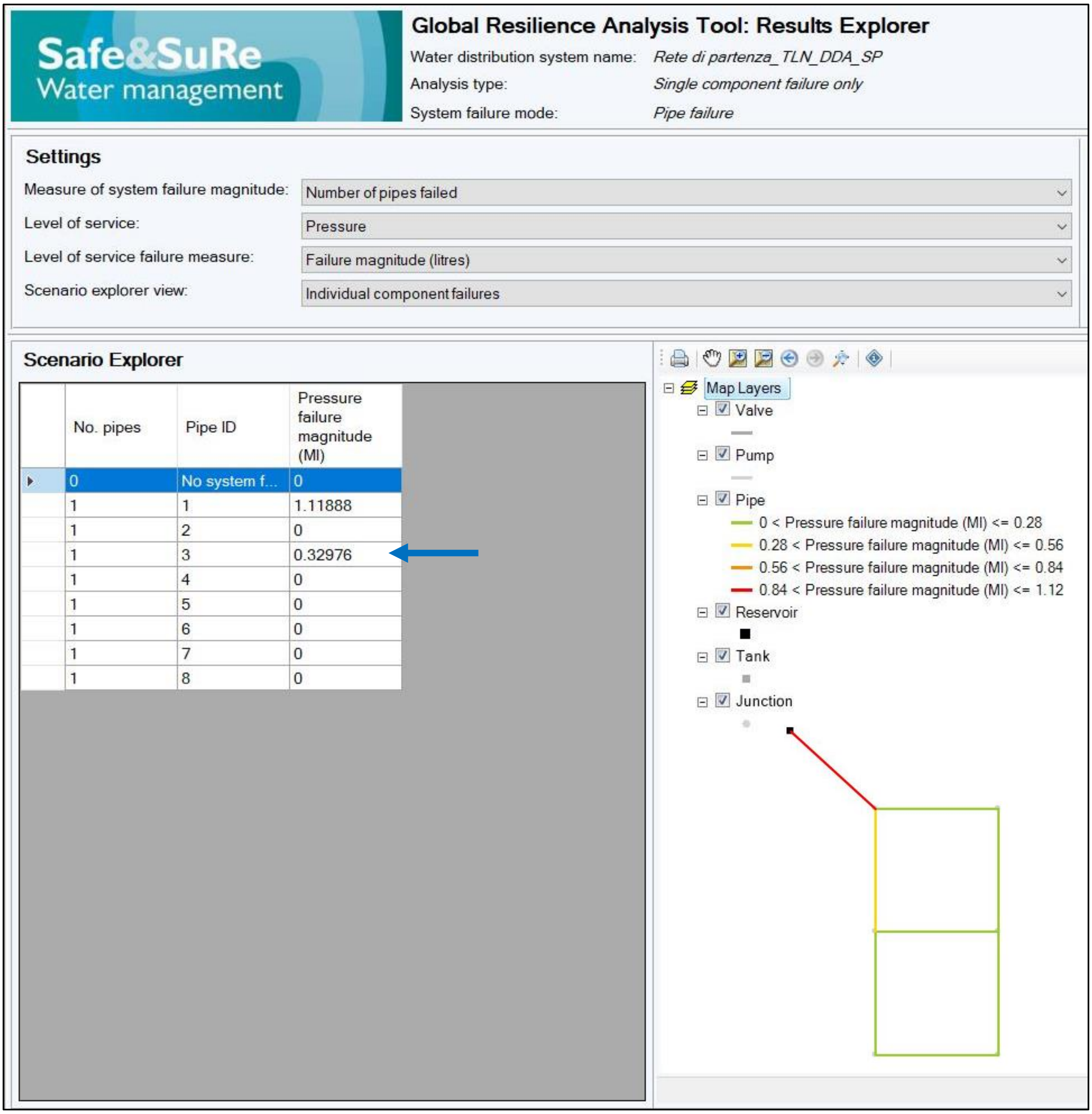


Figure 12 *Pressure failure magnitude (liters)*

The values of *Pressure failure magnitude (fraction)* are obtained dividing the Actual Demand of the node which has pressure less than 30 m (J_6) for the Total Actual Demand of the network:

Network Table - Nodes

Node ID	Base Demand LPS
Junc 2	27.7
Junc 3	27.7
Junc 4	33.3
Junc 5	75
Junc 6	91.6
Junc 7	55.5

$$\frac{Actual\ Demand_6(l/s)}{Total\ Actual\ Demand\ (l/s)}$$

$$= \frac{91.60}{2(27.7) + 33.3 + 75 + 91.6 + 55.5} = \frac{91.60}{310.8}$$

$$= \mathbf{0.294723}$$

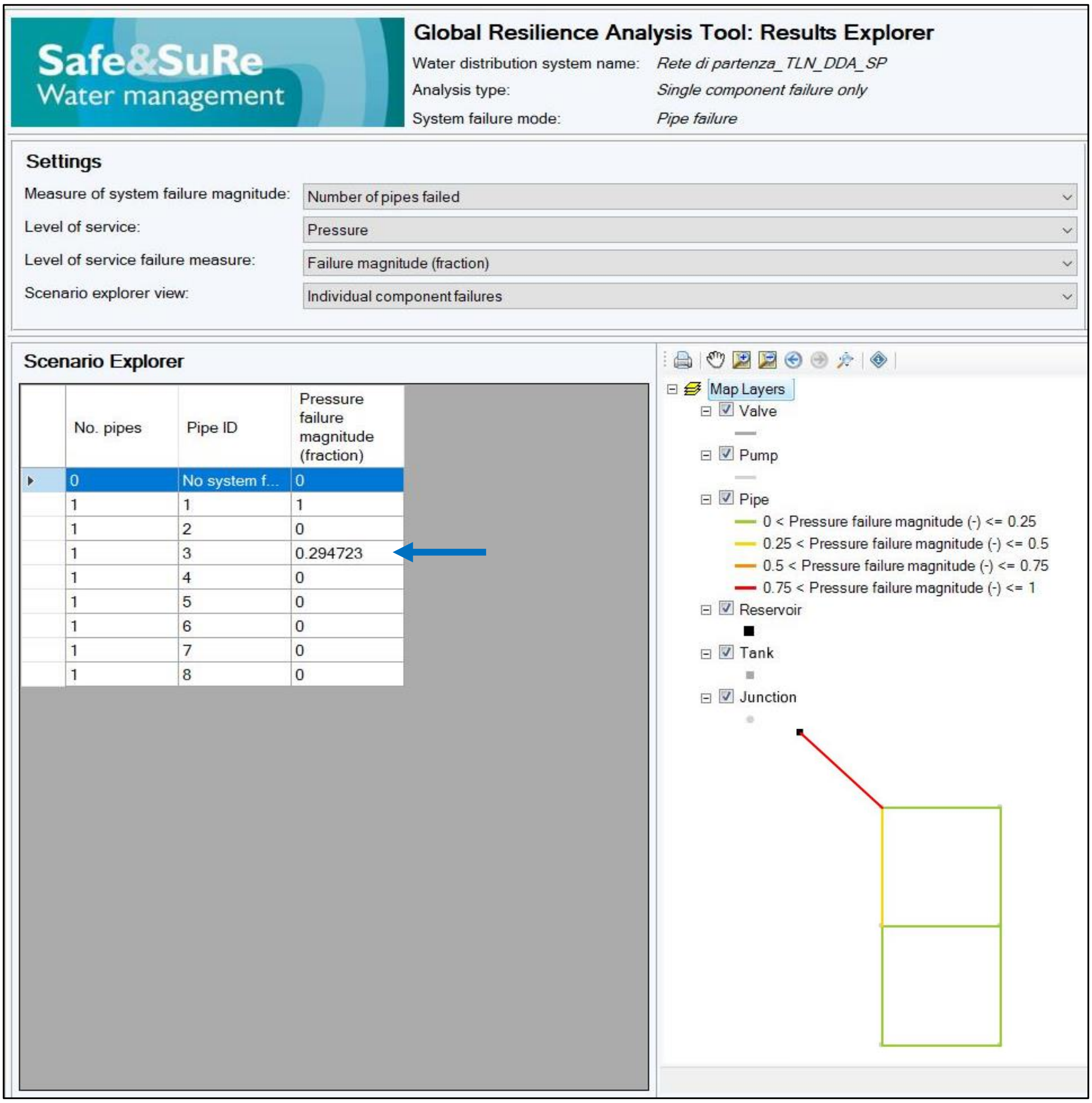


Figure 13 *Pressure failure magnitude (fraction)*

The level of service could also be expressed in terms of supply failure durations (hours) that are the duration for which at least one node in the system is subject to supply failure, based on the user specified pressure requirement (Figure 14).

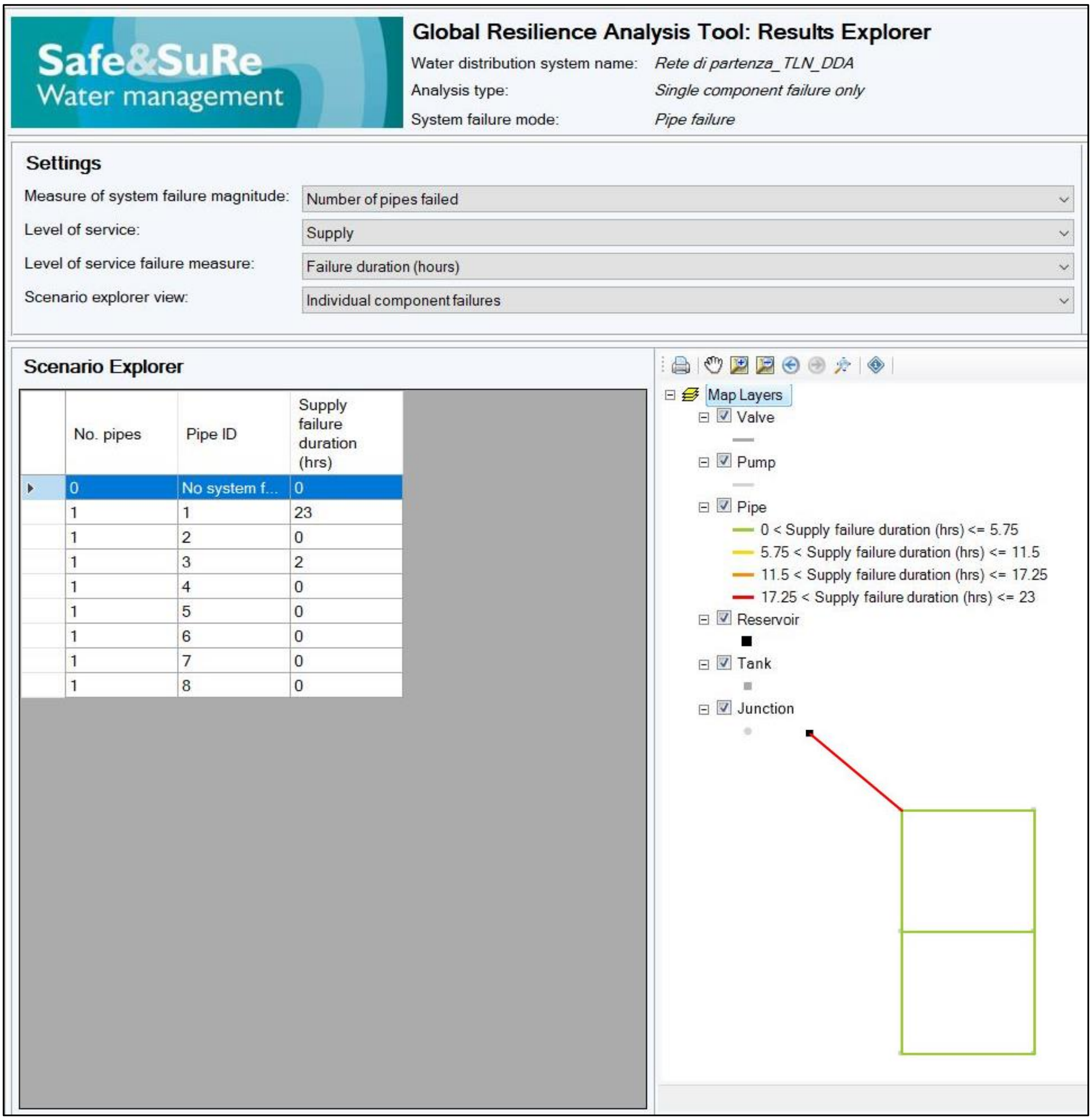


Figure 14 *Supply failure duration (hours)*

Supply failure magnitude, as the pressure failure magnitude, can be expressed in liters (Figure 15) or in fraction (Figure 16): in the first case is the total volume of demand not supplied, in the second case is the instantaneous fraction of demand not supplied during the simulation period.

The values of *Supply failure magnitude (liters)* could be expressed with the following formula:

$$S_{P3} = \left(Actual\ Demand_{J6}\ (l/s) - \left(Actual\ Demand_{J6}(l/s) \cdot \sqrt{\frac{Pressure_{J6}\ (m)}{Pressure_{lim}\ (m)}} \right) \right) \cdot 3600$$

$$\cdot 10^{-6} = \left(91.60 - \left(91.60 \cdot \sqrt{\frac{27.02}{30}} \right) \right) \cdot 3600 \ \cdot 10^{-6} = \mathbf{0.0168}\ \frac{\boldsymbol{Ml}}{\boldsymbol{h}}$$

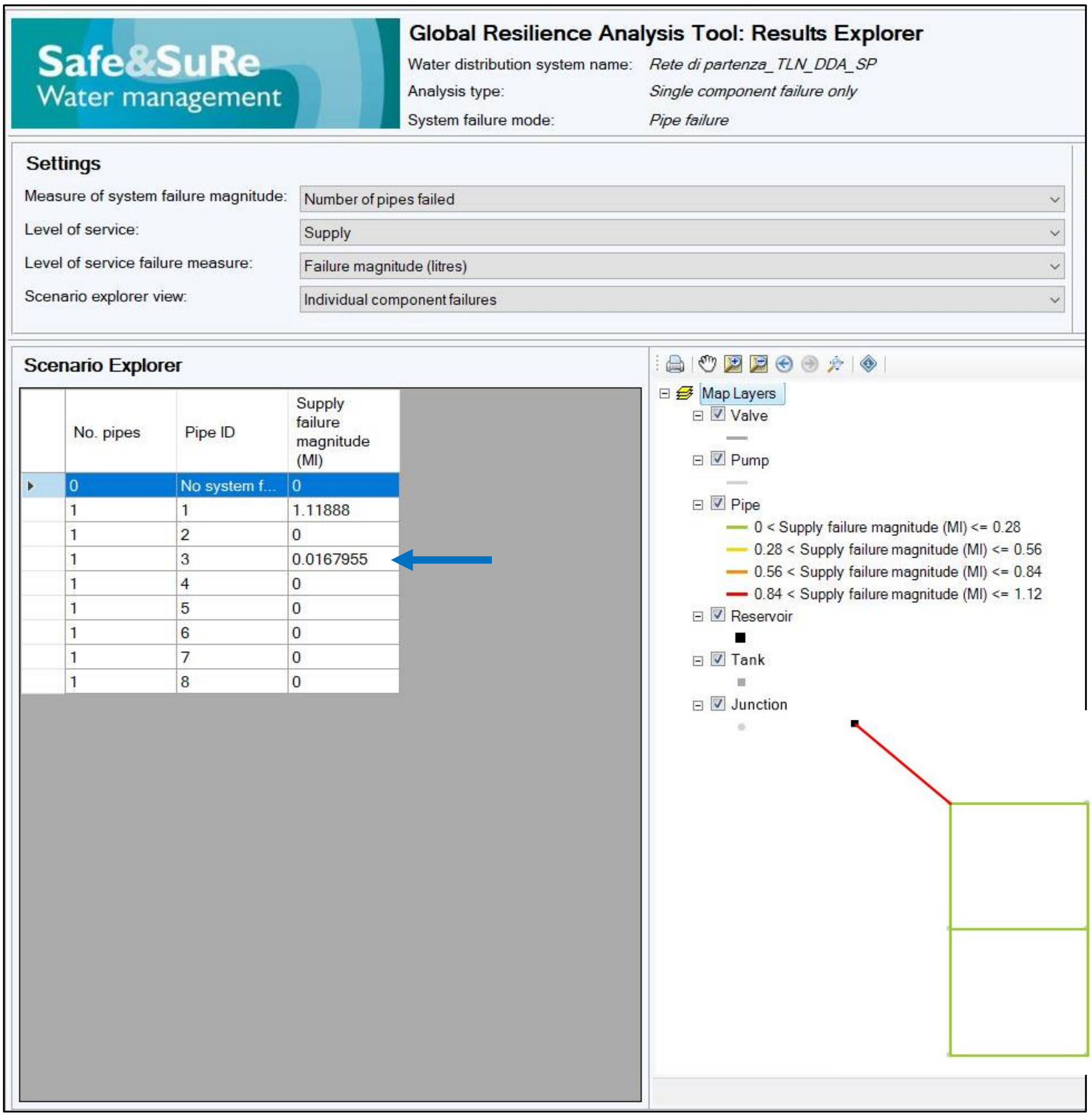


***Figure 15** Supply Failure magnitude (liters)*

The values of *Supply failure magnitude (fraction)* are obtained dividing the Supply failure magnitude (liters) of the node which has pressure less than 30 (S_{P3}) for the Total Actual Demand of the network transformed in Ml/h:

$$\frac{S_{P3}(Ml)}{Total\ Actual\ Demand\ (Ml)} = \frac{0.0168}{310.8 \cdot 3600 \cdot 10^{-6}} = \mathbf{0.01501}$$

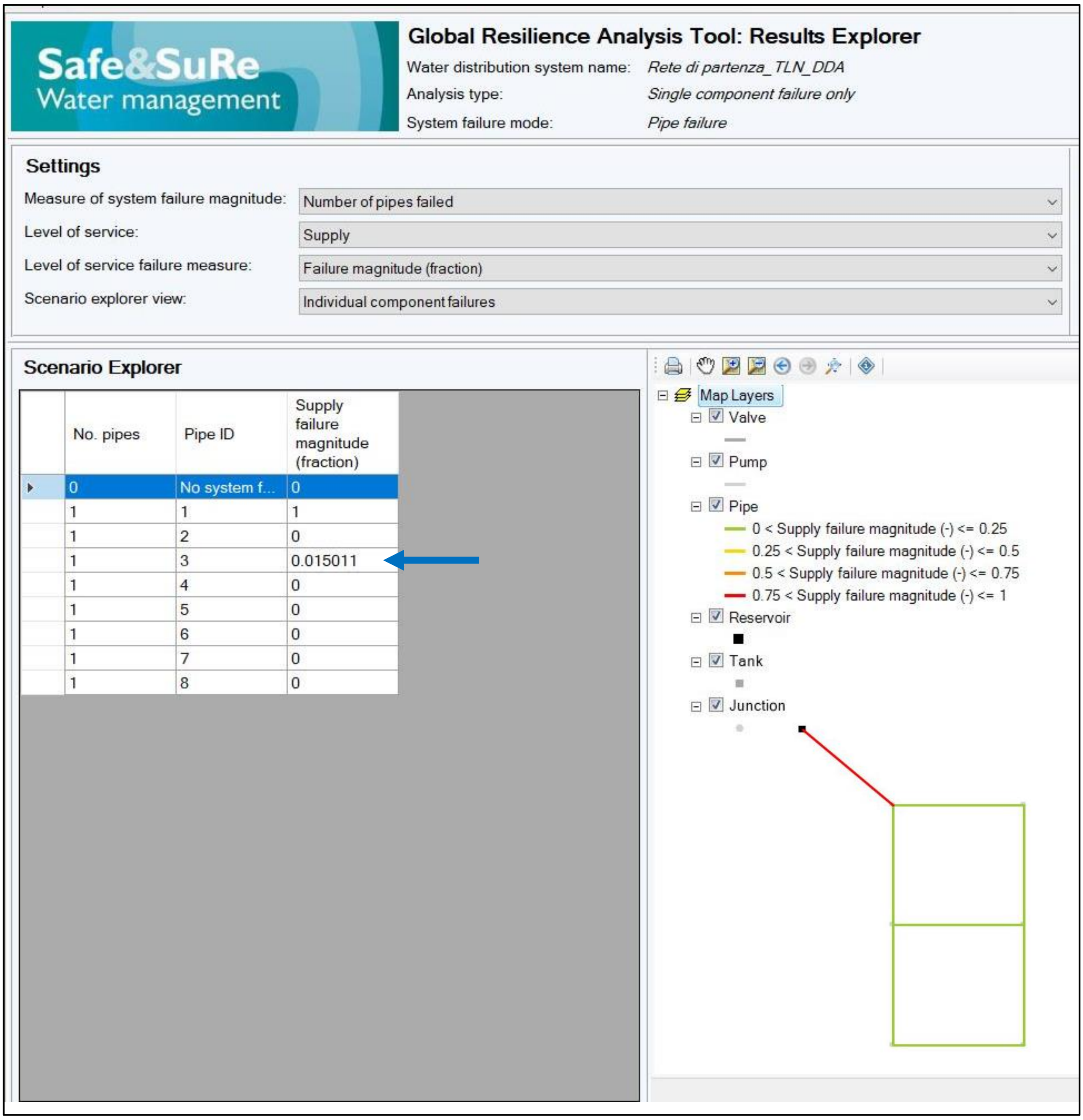


Figure 16 *Supply Failure magnitude (fraction)*

5.2.3 Epanet Toolkit results

SINGLE PERIOD

The first script created in MATLAB allows to calculate the Resilience and Failure Index of the starting network, which is solved hydraulically in Epanet using the Demand Driven approach.

In this case, the code provides a single Resilience and Failure value, as the simulation has been set on the *Single Period* option. As already mentioned in Paragraph 2, in the case of using the DDA mode, the first version of the formula proposed by Todini in the year 2000 was used, but updated to the mathematical conventions of the 2016 article (*Generalized Resilience and Failure Indices for Use with Pressure-Driven Modeling and Leakage*), namely:

$$I_r = \frac{\max\,[d^T(H-H_{des}),0]}{Q_0^T H_0 + Q_p^T H_p - d^T H_{des}} = 0.7306 \tag{14}$$

$$I_f = \frac{\min\,[d^T(H-H_{des}),0]}{d^T H_{des}} = 0 \tag{19}$$

The values, which is provided by the codes, are equal to I_r = 0.7306 and I_f =0. The Resilience and Failure Index value calculated with respect to a single instant of time, which in this case corresponds to midnight, that is to 0:00.

The resilience value is a positive and relatively high quantity, otherwise the failure value is equal to 0 that corresponds to a network configuration that feature a power surplus rather than a power deficit. In fact, these configurations are better described through I_r.

It is important to emphasize that, if this single temporal photograph on resilience and failure were considered, erroneous conclusions could be drawn and there would still be no certainty of having determined the indices in the most burdensome condition for the network.

In fact, at midnight, consumption along the network is more modest and the pressures are higher than what happens during the day, therefore, it is reasonable that the Resilience Index is higher than the daytime hours of maximum water demand.

As will be verified below, the variability of the 24-hour resilience and failure curves show that dwelling on the analysis of a single moment of time, even if it was the one of maximum consumption, does not guarantee that the most critical moment of the network in terms of availability of dissipable power is being taken into consideration. This demonstration will be carried out on the more complex network of Modena.

5.3 Modena

5.3.1 Description

In the following elaboration it has been supplied the primary water distribution network of Modena through a model of the net in which have already been inserted the data related to the layout of the net and to the water consumption. Such net has been previously used with the aim to find the optimal dimensioning in hydraulic and economic terms. In particular, the following phases have been carried out: optimal dimensioning of the water distribution network, optimization of the pumping systems, districtualization of a water distribution network and analysis of the quality of the distributed water.

As a result of these analyses, the optimized network of Modena has been used in the following thesis work. The hydraulic scheme of the network and its topological description are shown in Figure 17:

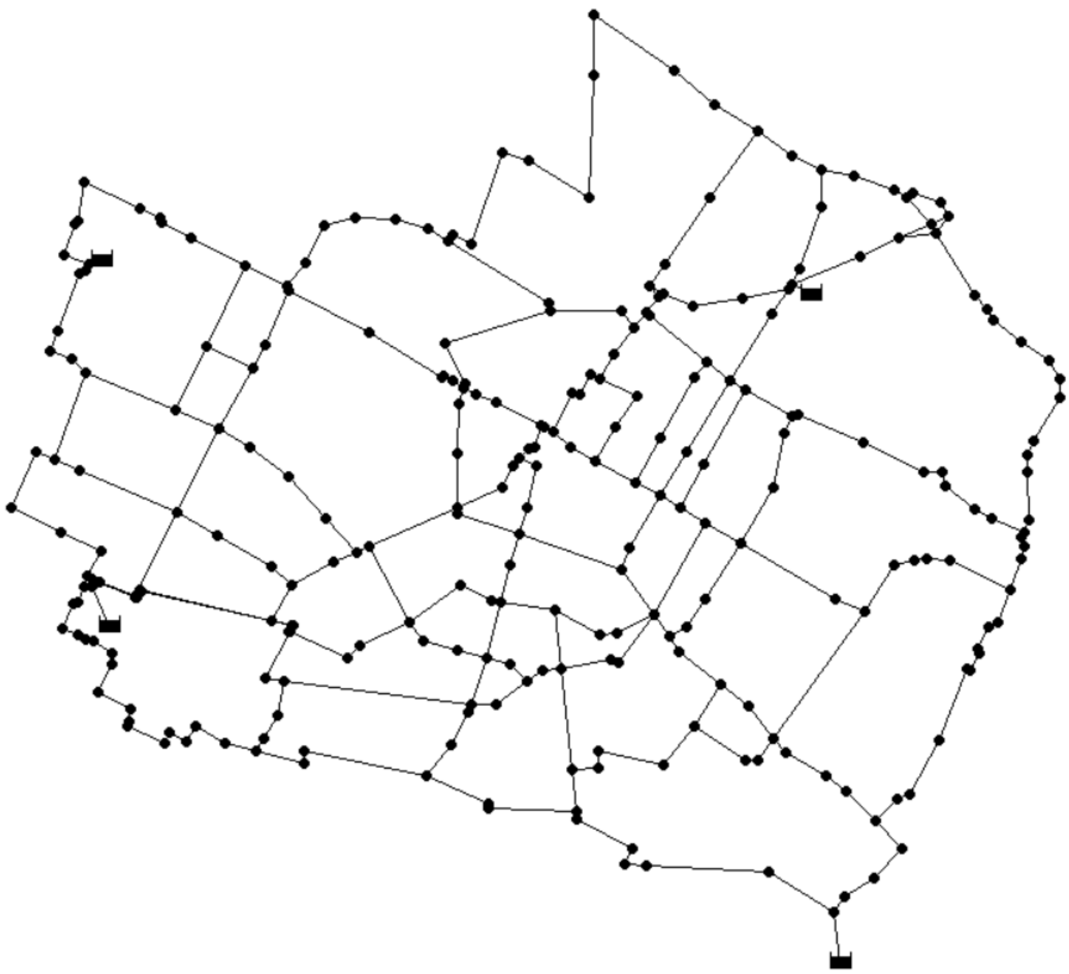


Figure 17 *Modena network*

The network is made up of 268 nodes and 317 pipes and it is fed by four entry point, that are Reservoir R_{269}, Reservoir R_{270}, Reservoir R_{271}, Reservoir R_{272}, with hydraulic load respectively equal to 72 m, 73.80 m, 73 m, 74.50 m. It is specified that inside the model there are no pumps or valves.

To each node of the network are associated: the elevation quota, the average annual demand, and the law of variation of water demand.

To every pipeline of the net are attributed: a diameter, a length, and a roughness. Pipe length ranges from a minimum of 1 m to a maximum of 1094.73 m, while the diameter values vary between a maximum of 400 mm and a minimum of 100 mm.

The Hazen Williams roughness coefficient equal to 130 $m^{0.37} s^{-1}$ was used for all network pipes and values of h_{min} and h_{des} equal to 5 and 20 m respectively were considered, because as said before, this network has been optimized and theoretically the required pressure equal to 20 m should be respected in all nodes because the diameters had been chosen to respect this condition.

The Base Demand (Figure 18), that is the average annual water consumption of the network users, is an input data, that is it has already been assigned to each node of the model.

In addition to the Base Demand, to the nodes of the net it has been associated also the Demand Pattern (Figure 19), that is the curve of temporal variation of the consumptions to the nodes, that is expressed through dimensionless coefficients.

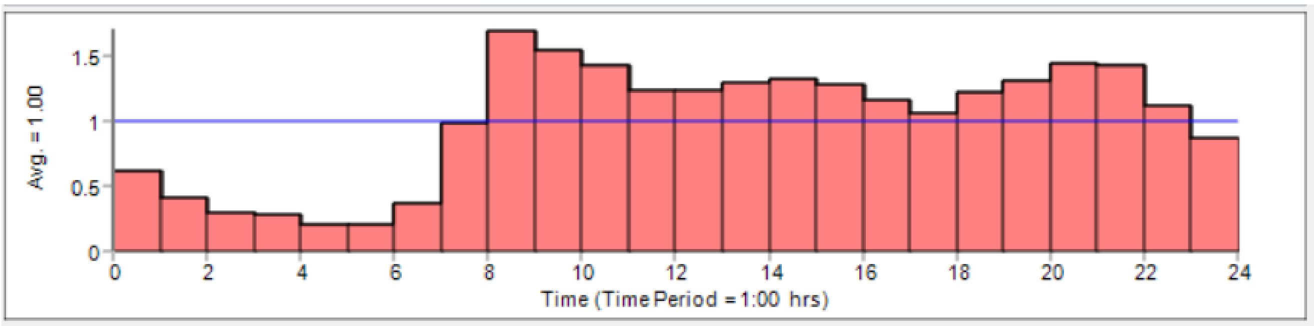


Figure 18 *Base Demand trend in 24 hours*

1	2	3	4	5	6	7	8	9	10	11	12
0,614	**0,410**	**0,288**	**0,284**	**0,202**	**0,205**	**0,370**	**0,985**	**1,691**	**1,544**	**1,423**	**1,235**

13	14	15	16	17	18	19	20	21	22	23	24
1,239	**1,291**	**1,325**	**1,278**	**1,166**	**1,059**	**1,223**	**1,309**	**1,437**	**1,433**	**1,114**	**0,874**

Figure 19 *Hourly coefficients of the Demand Pattern*

5.3.2 GRA Tool results

System failure mode: PIPE FAILURE

The type of analysis chosen is *Individual failures only*, which involves an analysis in which the effects of any single system component failure on the level of service delivery are evaluated. As for the synthetic network, the system failure chosen for the following study is the *pipe failure*, specifically 317 pipes were close one at a time and this failure was simulated from the first hour, with a duration of 24 hours and the minimum allowable pressure equal to 20 m.

The first level of service failure measures calculated is pressure failure durations (hours) in Figure 20:

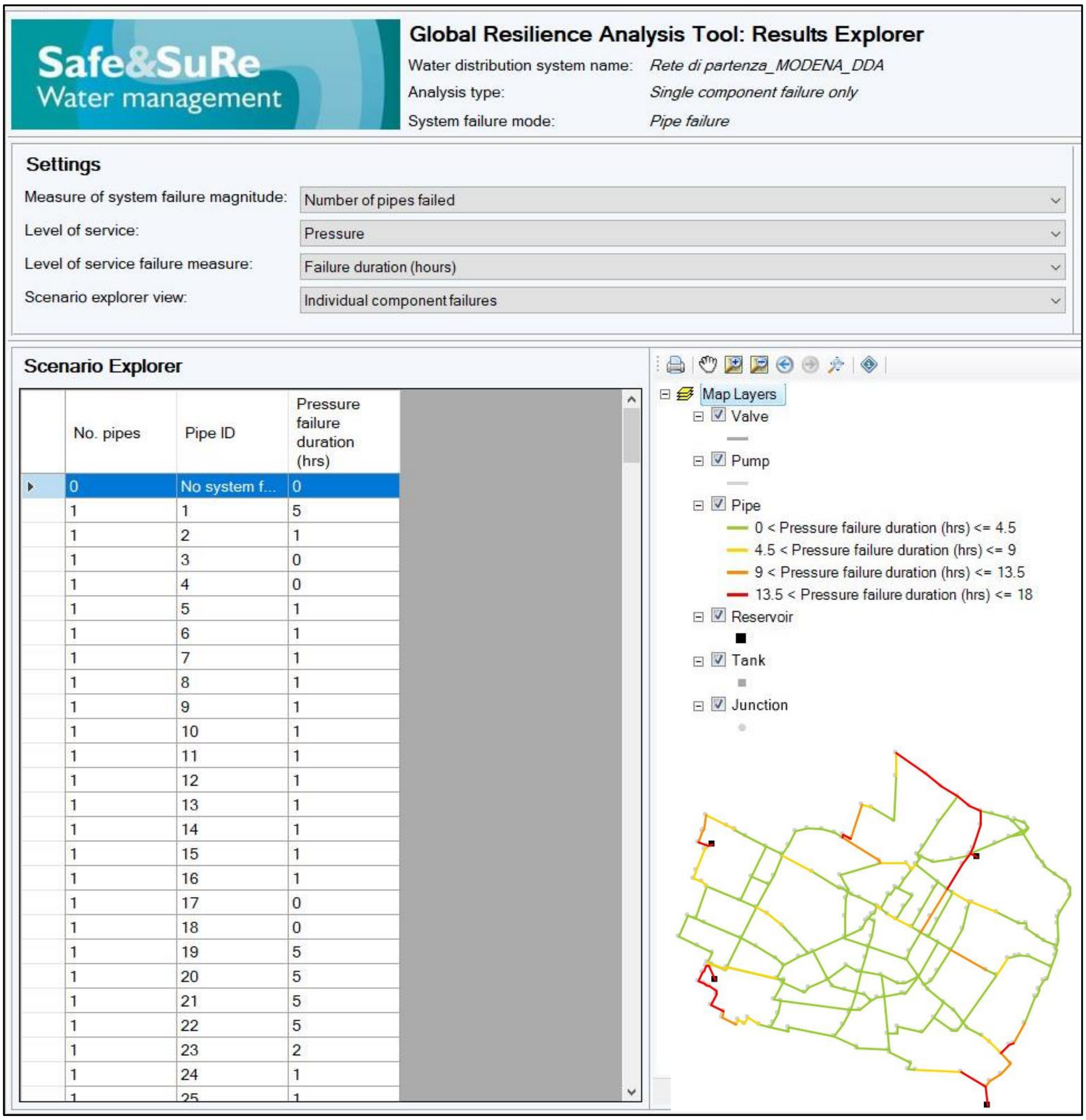


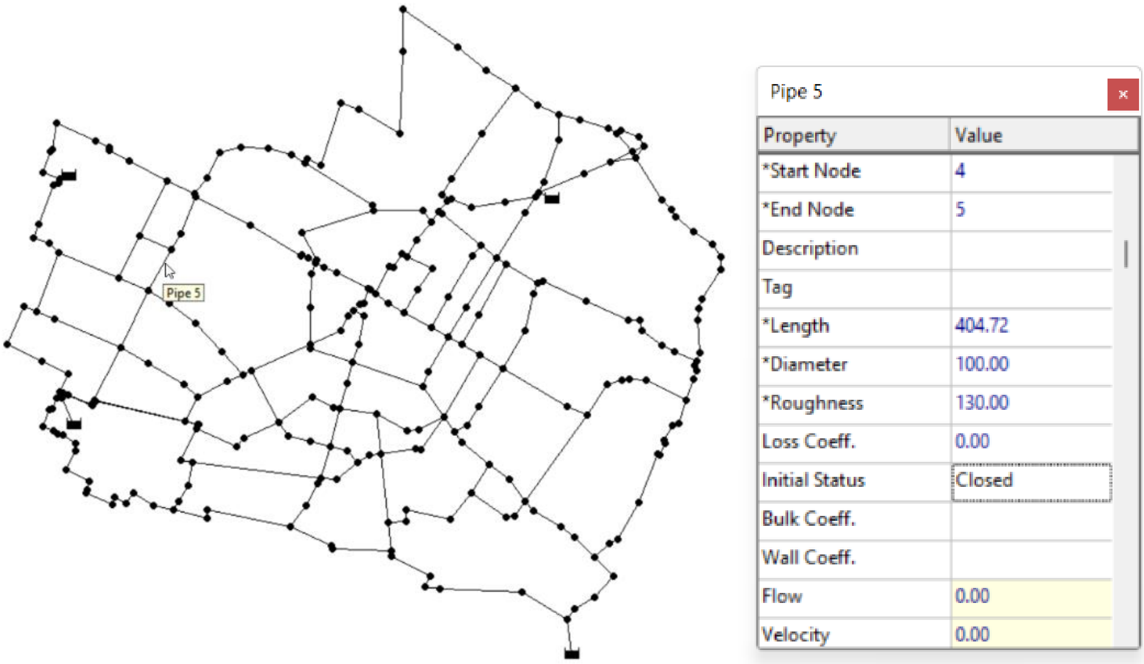
Figure 20 *Pressure failure duration (hours)*

Then is calculated the pressure failure magnitude that can be expressed in liters (Figure 21) or in fraction (Figure 22).

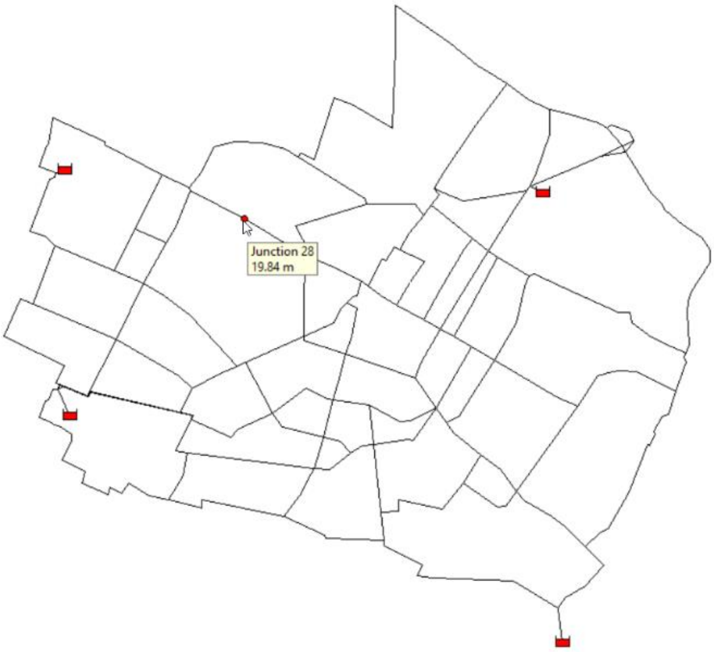
To understand where these results come from, the procedure adopted is reported below. For a system failure magnitude of *x*, pipe failure is modelled by setting *x* pipe statuses to *closed* in Epanet at the specified time and for the specified duration. For a better understanding of the procedure, it has been simulated the breakup of the **Pipe 5**.

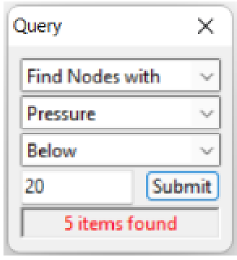
Pressure failure magnitude (liters):

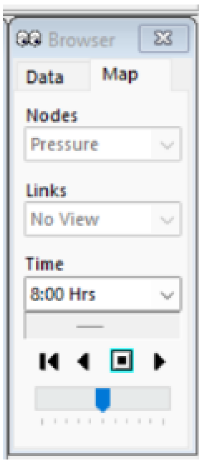
1. Close Pipe 5 and click *Run*



2. Check which node has the Actual Demand not satisfied (with pressure less than 20 m), in this case the Junction 28 at the time 8:00 am.







3. Calculate the Actual Demand of the Pipe 5 referred to the unsatisfied pressure with the following formula:

$$Actual\ Demand_{28}\ (l/s) \cdot\ 3600\ \cdot 10^{-6} = 7.07\ \cdot 3600\ \cdot 10^{-6} = \mathbf{0.0255}\ \frac{\boldsymbol{Ml}}{\boldsymbol{h}}$$

Junction 28

Property	Value
Description	
Tag	
*Elevation	36.15
Base Demand	7.11
Demand Pattern	
Demand Categories	1
Emitter Coeff.	
Initial Quality	
Source Quality	
Actual Demand	7.07
Total Head	55.99
Pressure	19.84
Quality	0.00

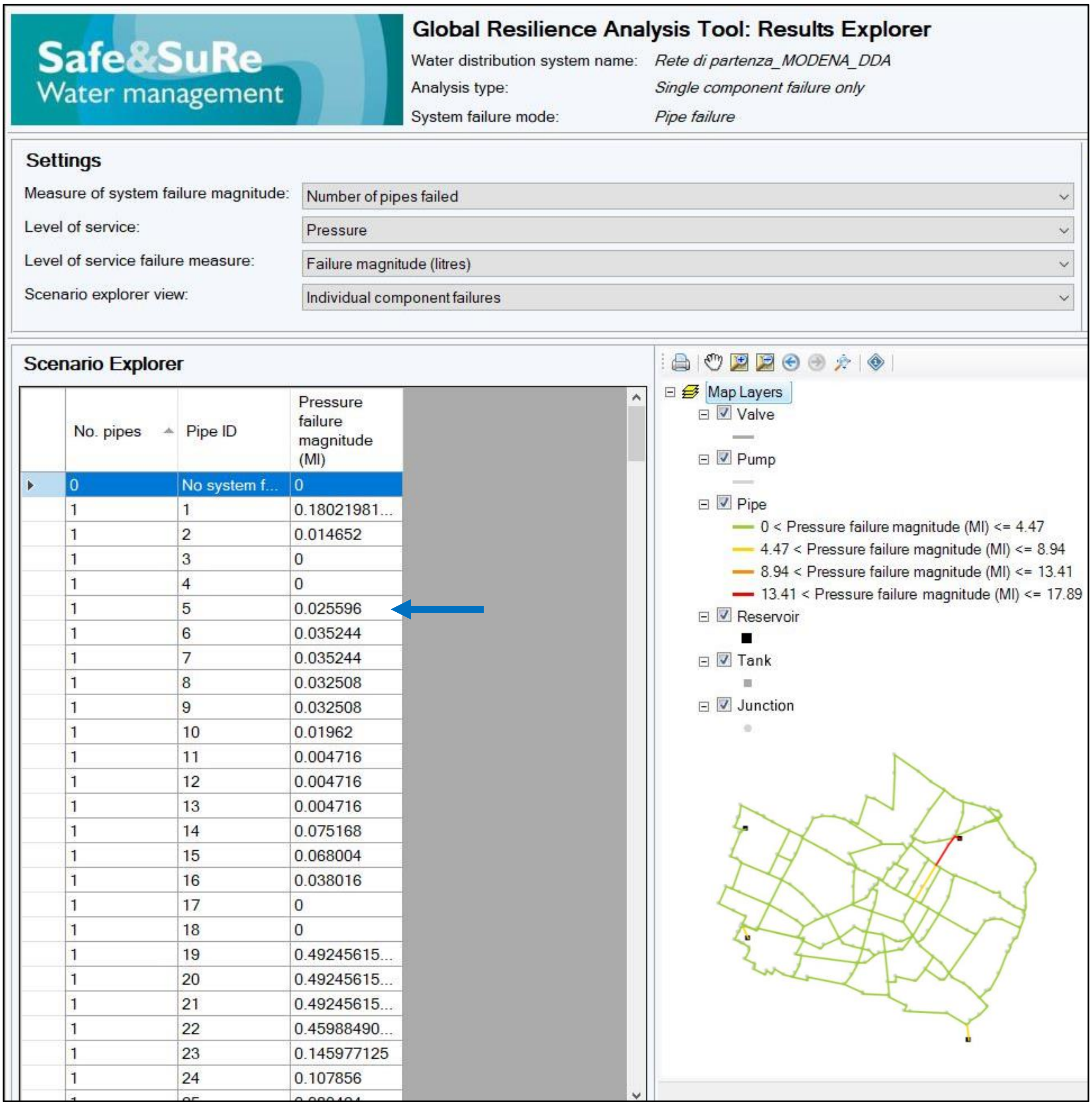


Figure 21 *Pressure failure magnitude (liters)*

Pressure failure magnitude (fraction):

Is the same as before with the difference that it calculates the unsatisfied Actual Demand and compares it with the Total Actual Demand requested by the network, not in the 24 hours, but in the temporal instant that corresponds in this case to 8:00 am, equal to 406.96 l/s (Figure 22).

$$\frac{Actual\ Demand_{28}(l/s)}{Total\ Actual\ Demand_{at\ 8:00}\ (l/s)} = \frac{7.07\ (l/s)}{406.96\ (l/s)} = \mathbf{0.0174}$$

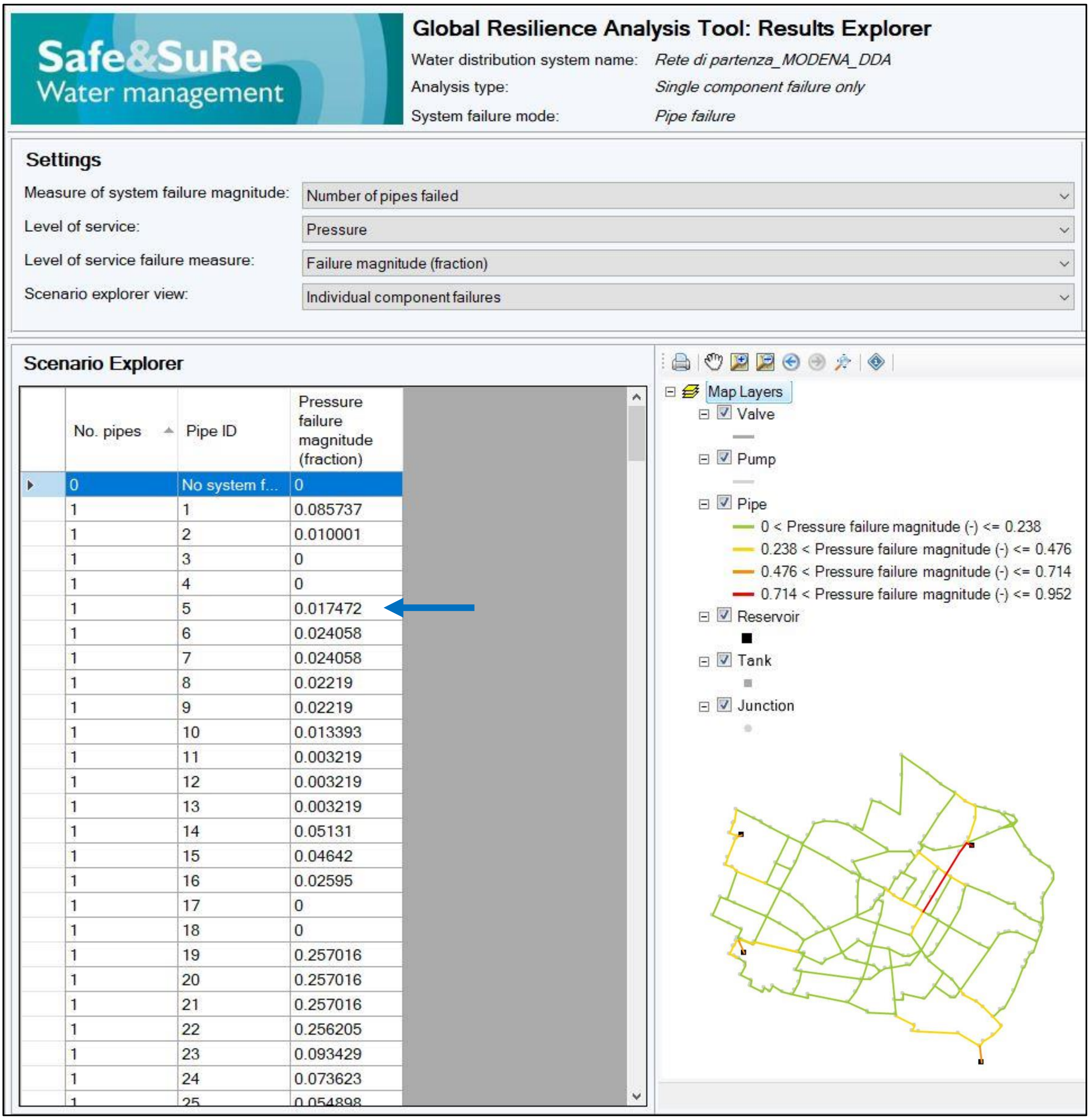


Figure 22 *Pressure failure magnitude (fraction)*

The second level of service failure measures calculated is <u>supply failure durations</u> (hours) in Figure 23. Also, it's possible, as before, to calculate the <u>supply failure magnitude</u>, that could be expressed in liters (Figure 24) or in fraction (Figure 25):

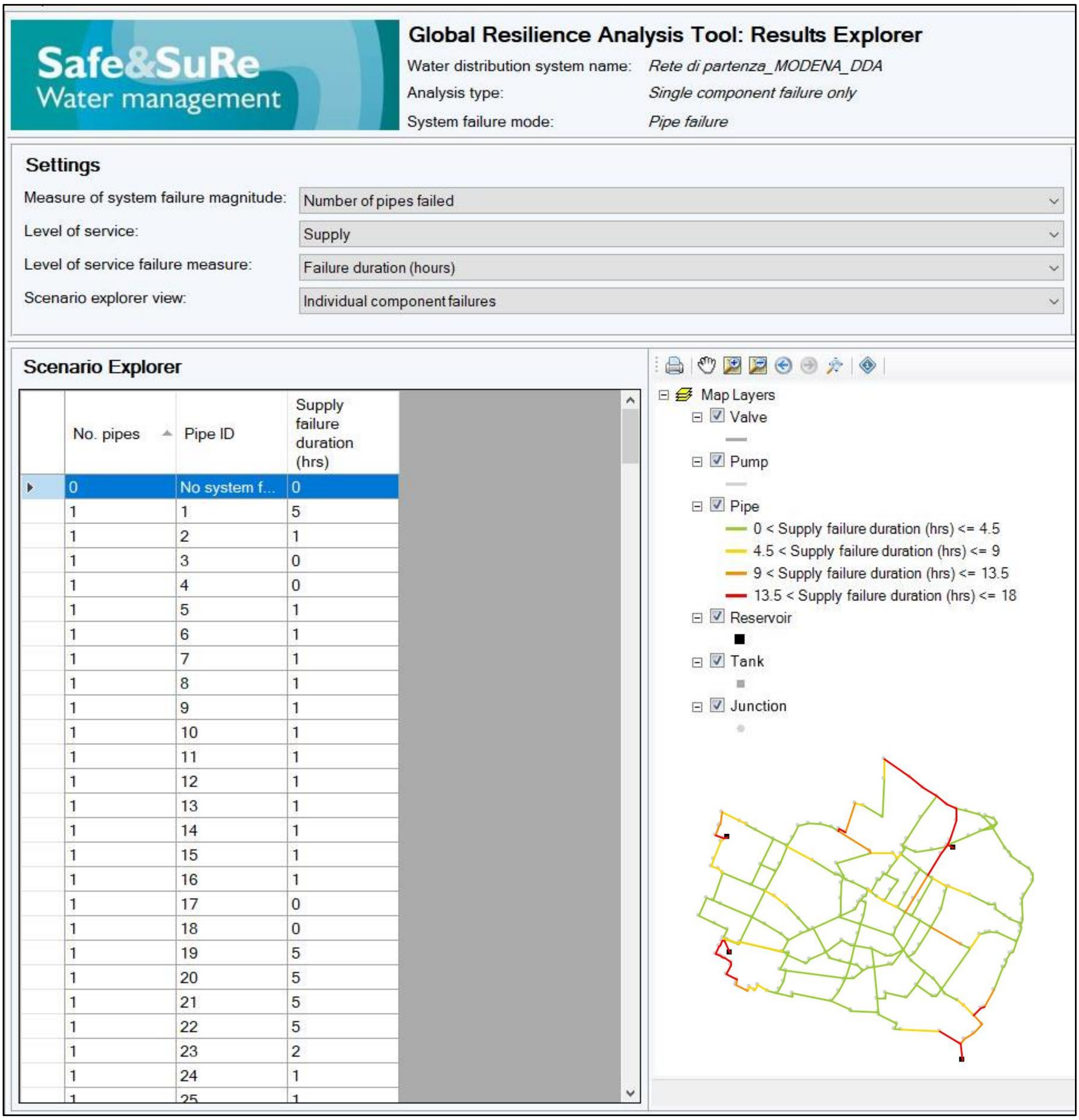


Figure 23 *Supply failure magnitude (hours)*

The values of *Supply failure magnitude (liters)* could be expressed with the following formula:

$$S_{P5} = \left(Actual\ Demand_{J28}\ (l/s) - \left(Actual\ Demand_{J28} (l/s) \cdot \sqrt{\frac{Pressure_{J28}\ (m)}{Pressure_{lim}\ (m)}} \right) \right) \cdot 3600$$

$$\cdot 10^{-6} = \left(7.07 - \left(7.07 \cdot \sqrt{\frac{19.84}{20}} \right) \right) \cdot 3600 \cdot 10^{-6} = \mathbf{0.0001} \frac{\boldsymbol{Ml}}{\boldsymbol{h}}$$

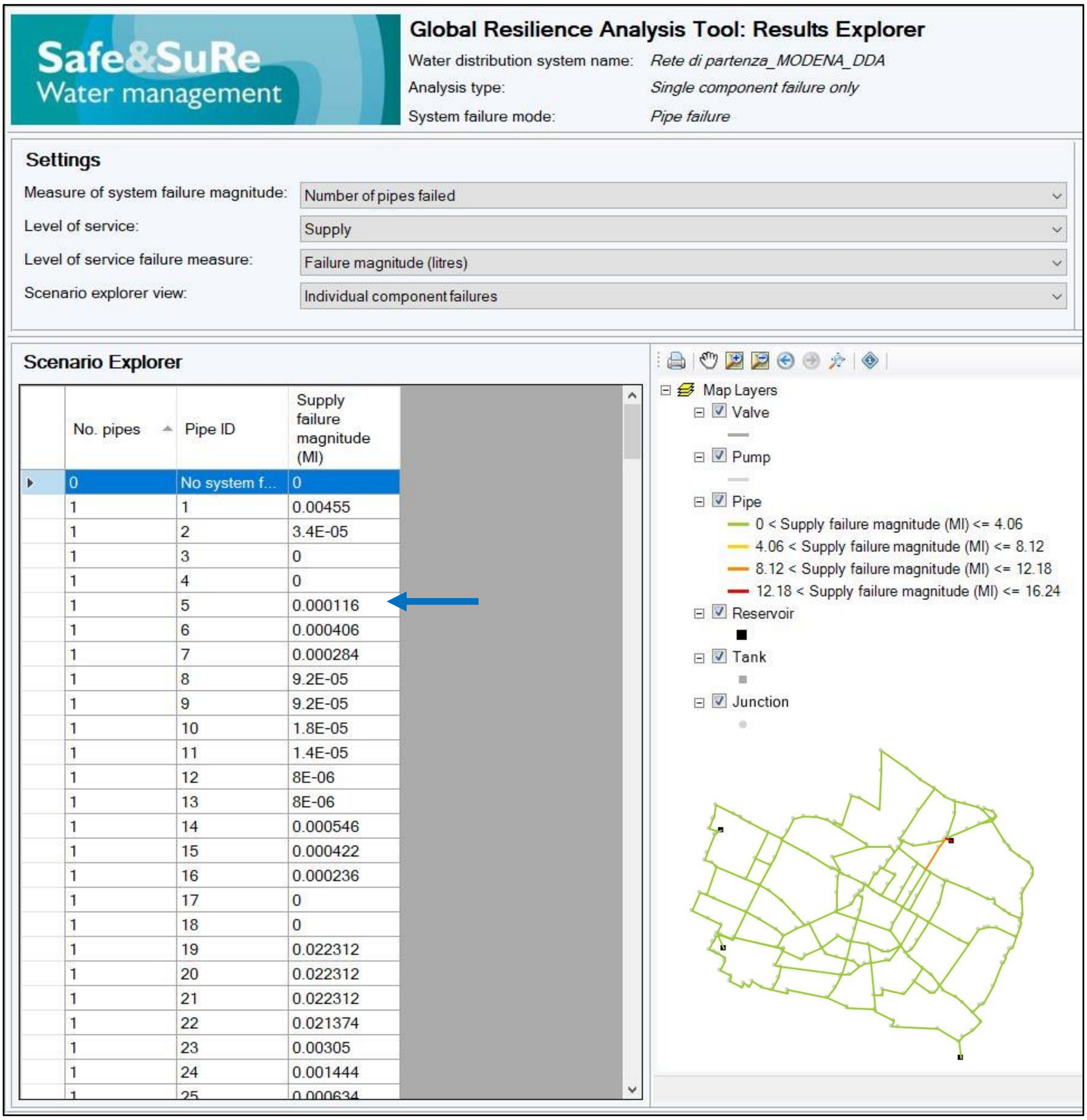


Figure 24 *Supply failure magnitude (liters)*

The values of *Supply failure magnitude (fraction)* are obtained dividing the Supply failure magnitude (liters) of the node which has pressure less than 20 (S_{P5}) for the Total Actual Demand of the network at 8:00 am, transformed in Ml:

$$\frac{S_{P5}(Ml)}{Total\ Actual\ Demand_{at\ 8:00}\ (Ml)} = \frac{0.0001}{406.96 \cdot 3600 \cdot 10^{-6}} = \mathbf{7.9 \cdot 10^{-5}}$$

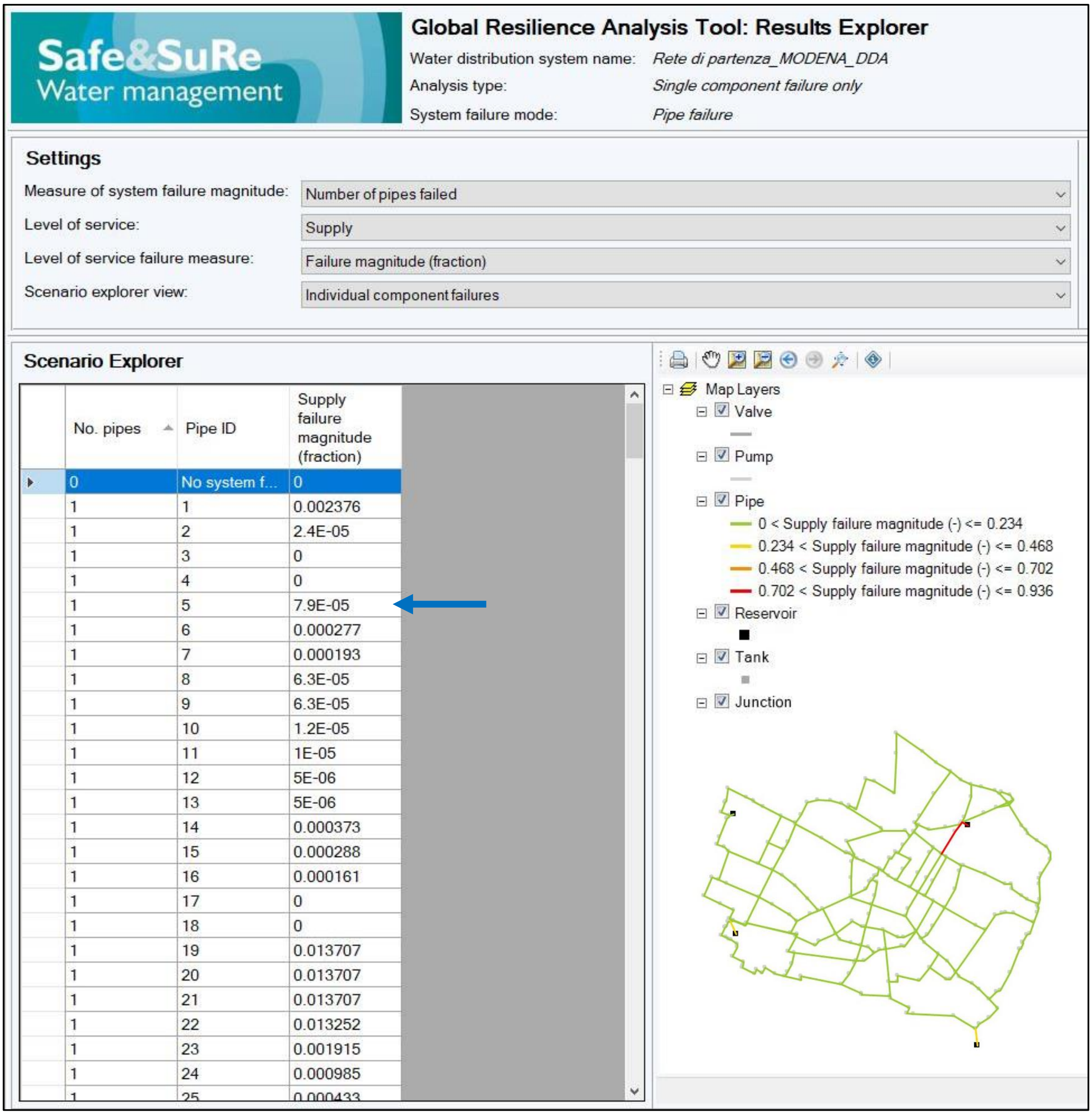


Figure 25 *Supply failure magnitude (fraction)*

5.3.3 Epanet Toolkit results

SINGLE PERIOD

The first script created in MATLAB allows to calculate the Resilience and Failure Index of the starting network, which is solved hydraulically in Epanet using the Demand Driven approach.

In this case, as for the synthetic case study, the code provides a single Resilience and Failure value, as the simulation has been set on the *Single Period* option, in particular the values are calculated with respect to a single instant of time, which corresponds to midnight, that is to 0:00.

The formula used is that proposed by Todini in the year 2000, but updated to the mathematical conventions of the 2016 article (*Generalized Resilience and Failure Indices for Use with Pressure-Driven Modeling and Leakage*):

$$I_r = \frac{\max\,[d^T(H-H_{des}),0]}{Q_0^T H_0 + Q_p^T H_p - d^T H_{des}} = 0.7217 \tag{14}$$

$$I_f = \frac{\min\,[d^T(H-H_{des}),0]}{d^T H_{des}} = 0 \tag{19}$$

The value of the Resilience Index calculated with respect to midnight, is a positive and relatively high quantity, and the Failure Index is equal to 0 that corresponds to a network configuration that feature a power surplus rather than a power deficit.

EXTENDED PERIOD

Demand Driven Analysis

As mentioned for the synthetic case, even if the expressions for calculating the Resilience and Failure Index were formulated thinking at a single instant of time, knowing the variability of these indices, it is more reasonable that these are calculated with respect to a succession of time steps, not knowing a priori when the most critical condition will arise.

For these reasons, keeping unchanged the Demand Driven analysis method and formulas (14) and (19), it was decided to derive the trend of the Resilience and Failure Index during the day, thus setting a simulation in *Extended Period*, such as to obtain a value of resilience and failure for each time step of analysis, that is, for each hour of the day; Figure 26 and 27 shows the variation of the I_r and I_f values throughout the day.

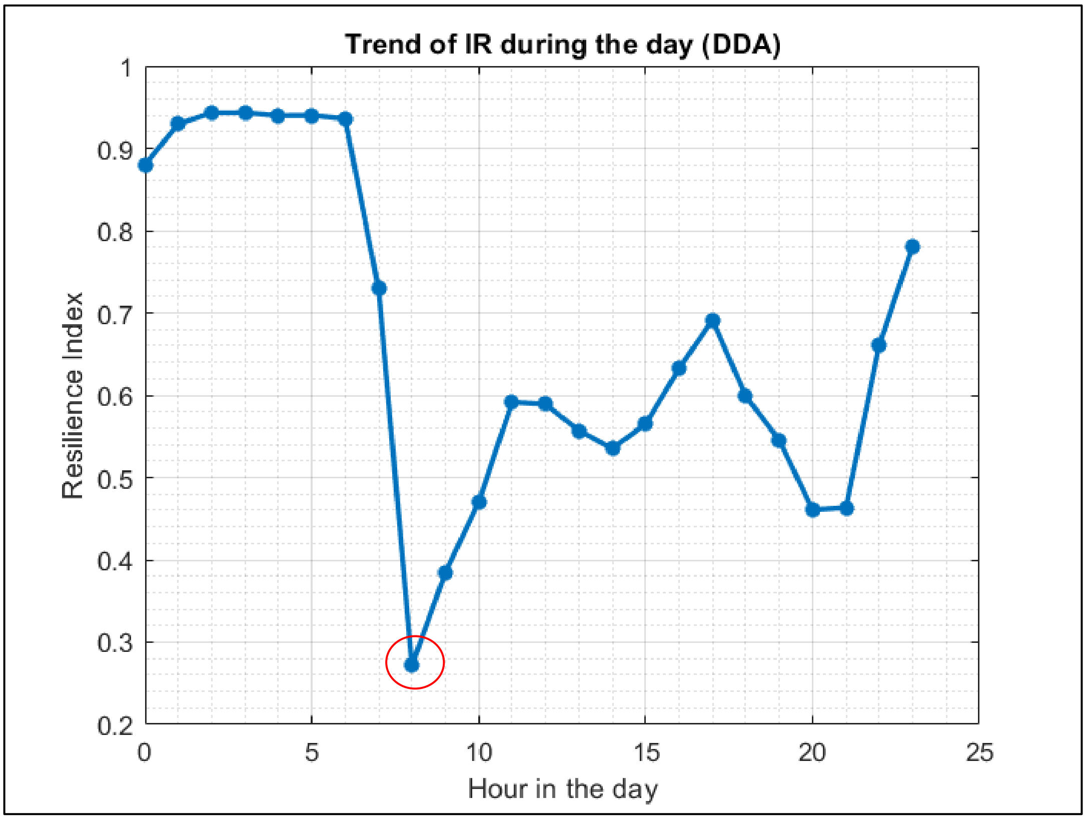


Figure 26 *Trend of the Resilience Index over 24 hours in the DDA case*

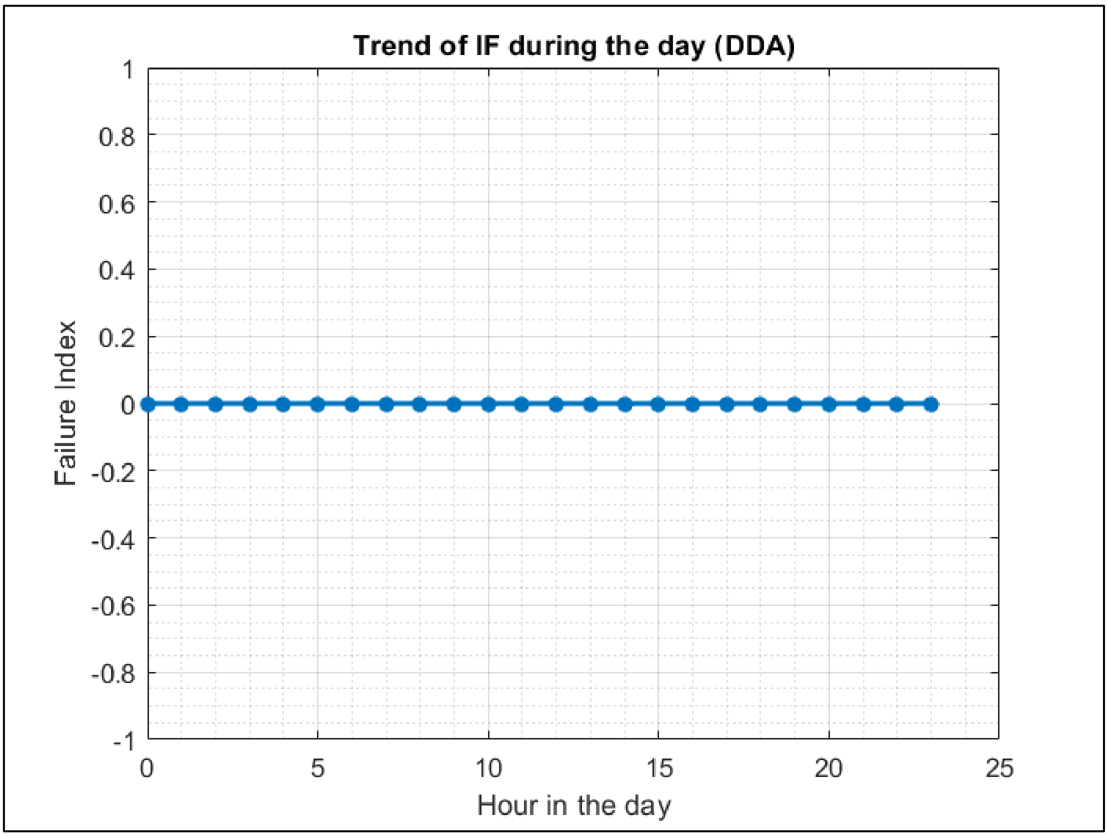


Figure 27 *Trend of the Failure Index over 24 hours in the DDA case*

This variation curve shows that in DDA mode, i.e., when it is assumed that the demand at the nodes is always satisfied, the Failure Index is always zero, while the Resilience Index is characterized by reaching lower peaks in correspondence with the time bands in which the demand of withdrawal by users is greater, that is between 8 am and 9 am (worst scenario shown with a red circle), at midday, and between 8 pm and 9 pm.

This means that in the hours of maximum consumption, the resilience decreases, and then, after the most critical hours for consumption, the network is affected by a resilience, which tends to increase again. It could also be interesting to demonstrate this concept by comparing the Base Demand with the Resilience Index (Figure 28).

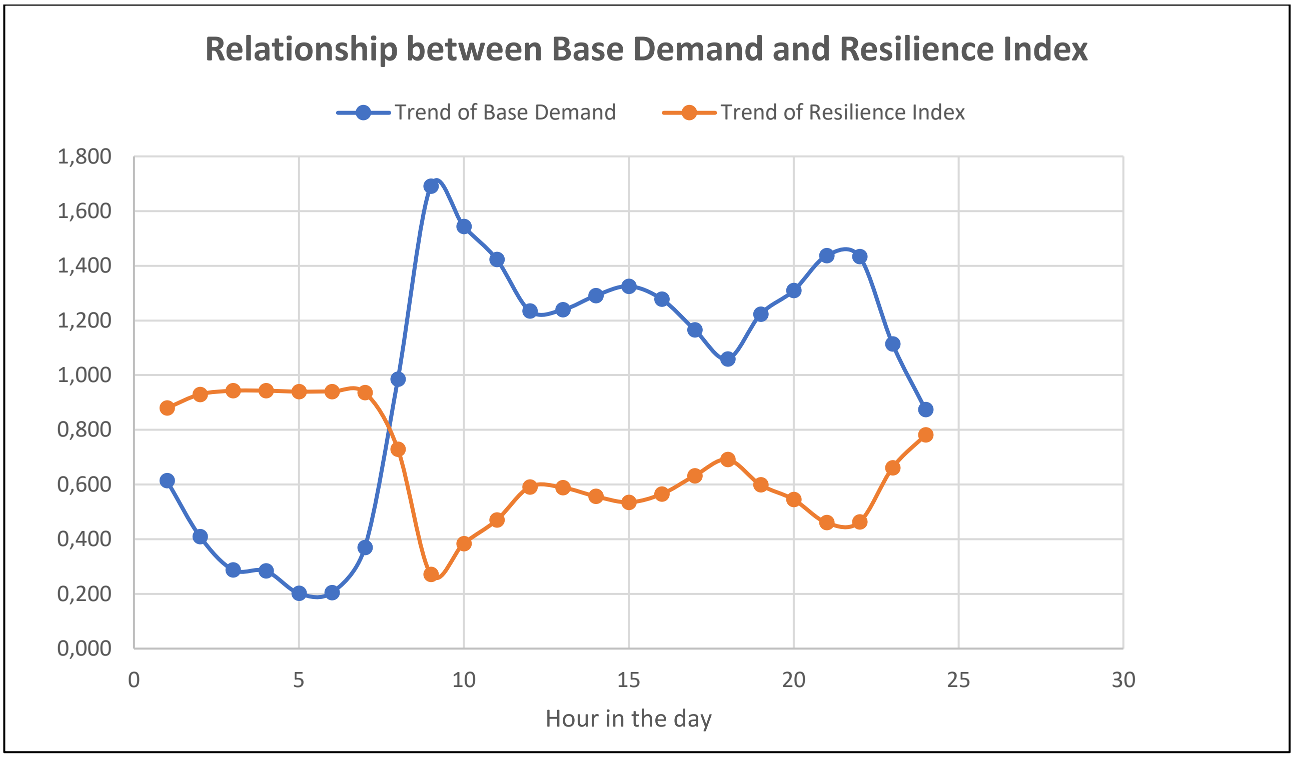
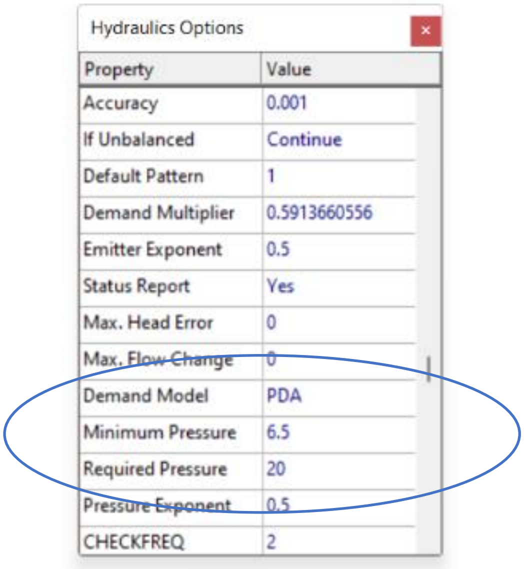


Figure 28 *Trend of Resilience Index compared to the trend of Base Demand*

Pressure Driven Analysis

Furthermore, it was quantified the Resilience and Failure Index along the day by imposing in Epanet the Pressure Driven simulation mode. To do this, two appropriate parameters had to be set:



Hydraulics Options

Property	Value
Accuracy	0.001
If Unbalanced	Continue
Default Pattern	1
Demand Multiplier	0.5913660556
Emitter Exponent	0.5
Status Report	Yes
Max. Head Error	0
Max. Flow Change	0
Demand Model	PDA
Minimum Pressure	6.5
Required Pressure	20
Pressure Exponent	0.5
CHECKFREQ	2

The term *Required Pressure* is to be understood as that value above which it is always possible to guarantee the withdrawal of all that the users require.

While the term *Minimum Pressure* corresponds to the value below which there is no possibility of withdrawal.

It is possible to quantify the values of Resilience and Failure Index proposed by Todini in 2016, designed for an analysis in terms of Pressure Driven, using the latest version of the formula (*Generalized Resilience and Failure Indices for Use with Pressure-Driven Modeling and Leakage*):

$$I_r = \frac{\max\,[q_{user}^T H - d^T H_{des}, 0]}{Q_0^T H_0 + Q_p^T H_p - d^T H_{des}} \tag{18}$$

$$I_f = \frac{\min\,[q_{user}^T H - d^T H_{des}, 0]}{d^T H_{des}} \tag{20}$$

These formulas provide the same trend of the Resilience and Failure Index in the 24 hours in DDA (Figure 26 and 27). This is explained by the fact that the network has been optimized so that the minimum pressures do not go below 20 m, therefore the trend of the graphs is the same, as the user withdrawal is always satisfied in both cases, therefore, the approach PDA leads to DDA.

Comparison between DDA and PDA

The numerator of the formula (18) is characterized by the differentiation between the terms $quser$ and d, as opposed to what happens for the formula (14) considered previously.

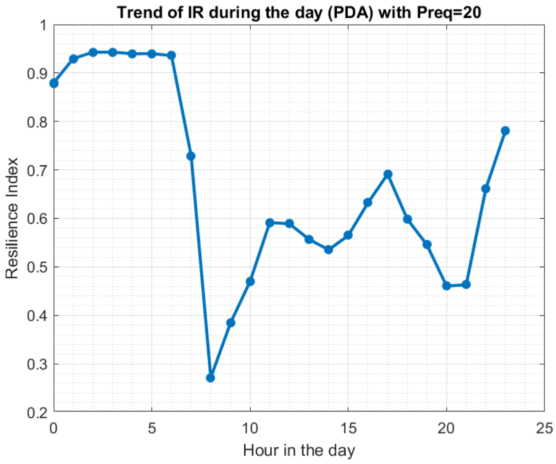
Specifically, d is the Actual Demand of the DDA simulation, therefore, it represents the theoretical flow required to the nodes, that is the one that the users would like to be able to take. From a technical point of view, d is to be understood as $d = BD \cdot Demand\ Pattern$, that is, as the product between the Base Demand and the Demand Pattern coefficients, different for each instant of simulation time. In the Demand Driven approach, the Actual Demand is given by the sum between consumption and water losses, but, since in this case study it was decided not to model the losses, the Actual Demand simply remains the same as the above product. Similarly, the notation $quser$ refers to the Actual Demand calculated in the PDA simulation, for which the term corresponds to the flow rate assigned to the nodes.

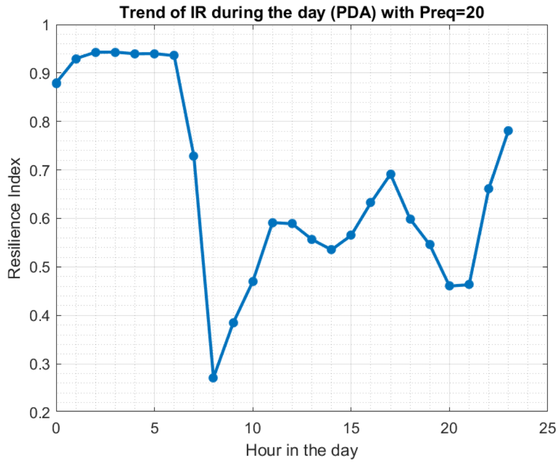
It is also important to remember that the Todini Index was originally designed to be used in a water network project context, therefore, the goal was to search for an optimal configuration, such as to obtain always positive resilience values.

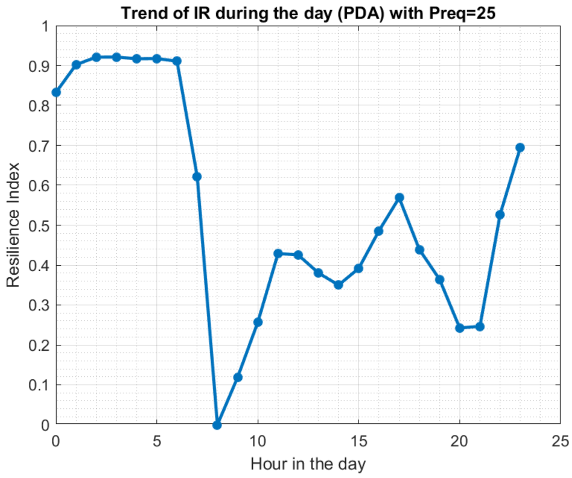
Consequently, when formula (18) is used to evaluate the performance of an already existing network, it may occur that the values in the numerator, given by the difference between the flow rate that can be taken $(quser)$ for the actual hydraulic load at knots and the desired flow rate (d) for the required hydraulic load are also negative. Therefore, the "max" function has been inserted, able to reset negative values when $quserH < dHdes$. The numerator of the formula becomes negative when $H < Hdes$, that is, when the actual hydraulic load is less than the desired hydraulic load.

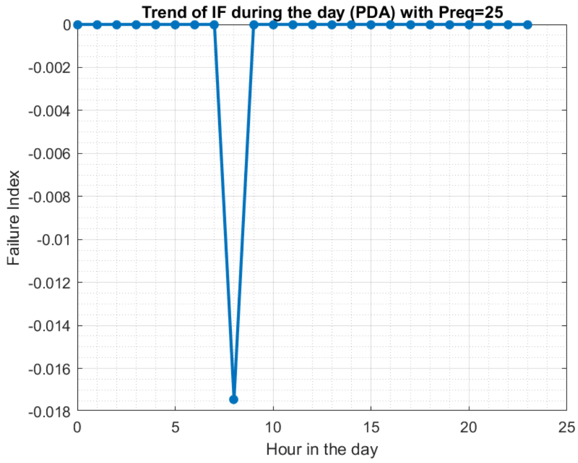
Considering what has been said, since the initial network configuration does not allow to clearly appreciate the differences between the two simulation approaches, to allow comparison, it was decided to temporarily change the Required Pressure value set within the PDA mode.

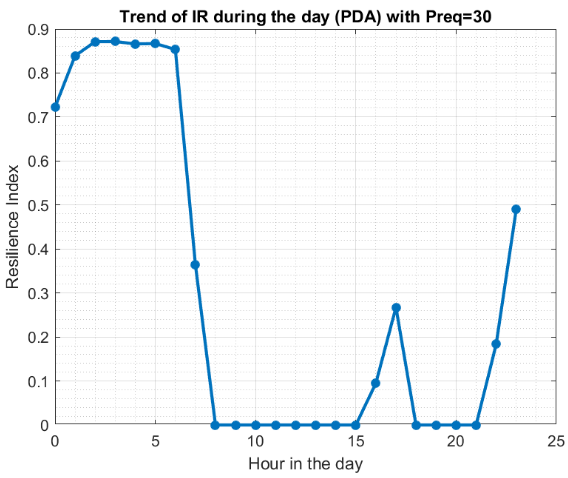
First, the value was increased from 20 to 30 m, in such a way as to penalize more the situation in terms of withdrawal from the nodes and to lower the Actual Demand calculated in the PDA simulation. Later, it was decreased from 20 m at 10 m. It is important to specify that, by varying the Required Pressure, the values associated with the desired hydraulic load are also modified. The intermediate situation with values of Required Pressure equal to 15 m and 25 m, was also investigated. By applying these changes to the Epanet hydraulic settings, from the PDA simulation, obtained from the same MATLAB script, the following curves are obtained.

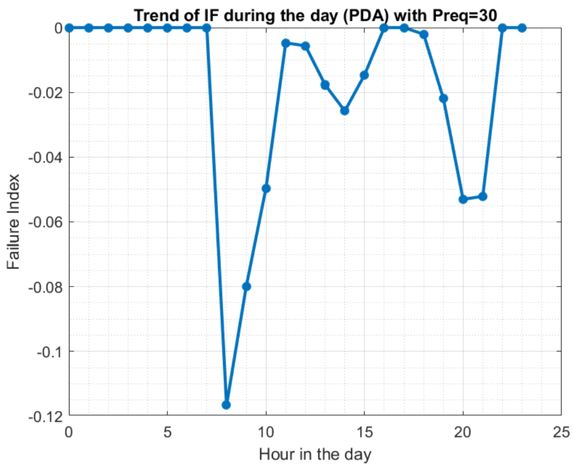




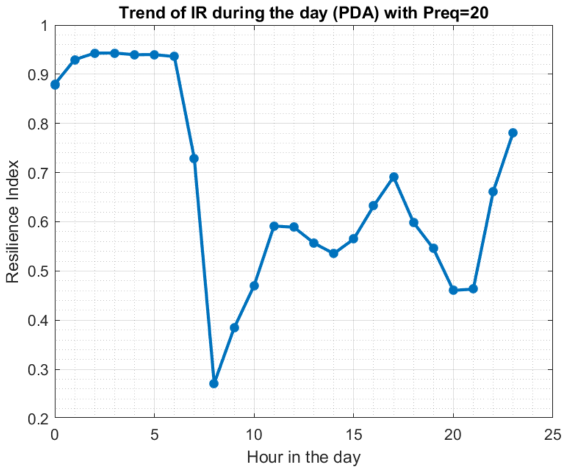


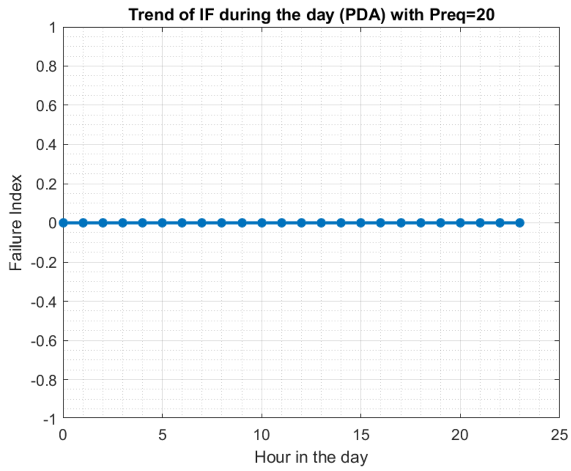


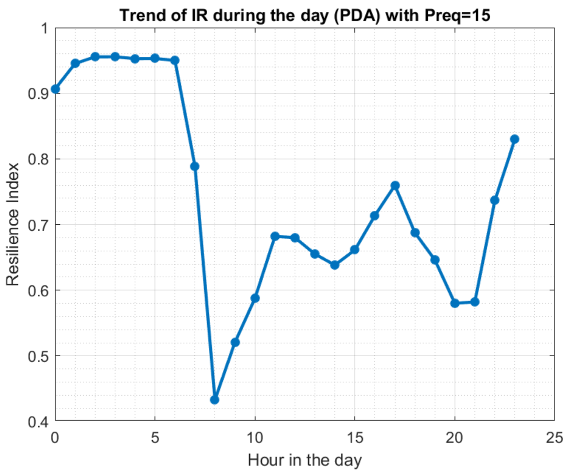


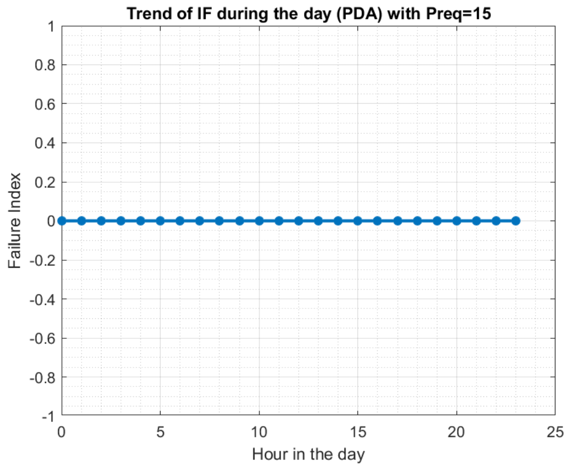


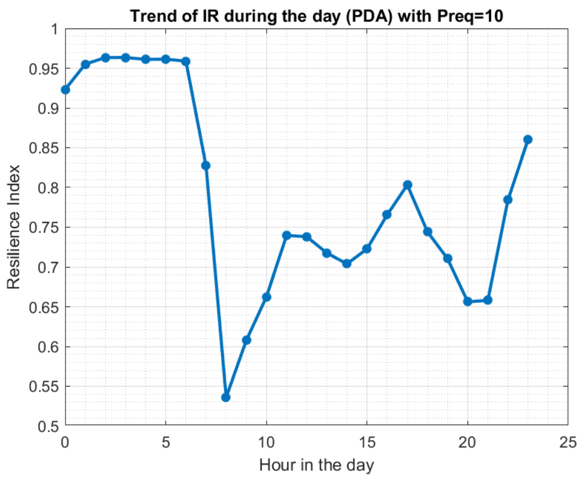
The increase of the Required Pressure to 25 m and 30 m caused a decrease of the Resilience Index and an increase of the Failure Index.

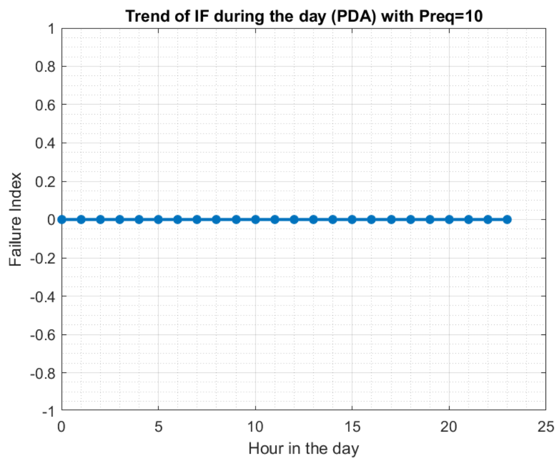












On the other hand, the reduction of the Required Pressure to 15 m and 10 m led to a situation where the Failure Index remain constant, equal to zero, and an improvement in the resilience of the network, the trend of which has the lower values, only in correspondence with the maximum consumption between 8 am and 9 am.

A graph that shows the Resilience and Failure Index trends for the four different Required Pressure values was also reported, to have a better view of the concept (Figure 29).

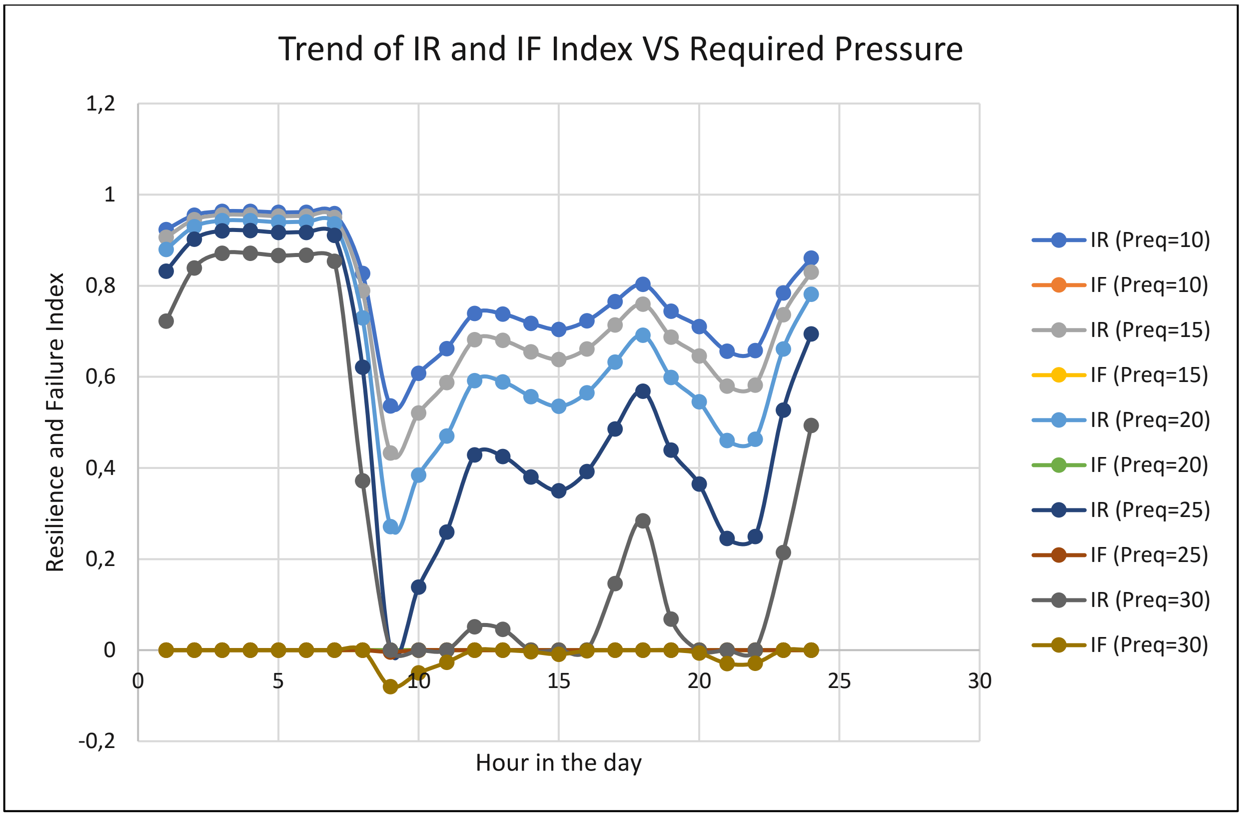


Figure 29 *Trend of Resilience and Failure Index with respect to the variation of Required Pressure*

This means that the adjustment of the Required Pressure is one of the possible aspects on which to act, to optimize the Resilience and Failure Index of the water network distribution.

With a view to carrying out a resilience sensitivity study, to understand what are the factors that most influence the variation, thanks to these results, it is already possible to deduce that the hydraulic simulation in PDA mode is more suitable for this purpose compared to that DDA.

In fact, as demonstrated, the PDA approach, allowing to act on parameters such as Required Pressure and Minimum Pressure, allows, as far as possible, to better adjust the resilience.

PIPE FAILURE

In this case, the stress has been modeled going to modify the state of the interested pipe from *Open* to *Closed* for the entire duration of the simulation, that is 24 hours. It has been created a MATLAB code, that, after to have hydraulically resolved the net of departure set in Epanet according to the mode PDA, it is able to return the various trends of the Resilience and Failure Index in the day.

These trends are different one from the other, because the script has been created to reproduce the progressive breaking of every single pipe of the network. The graphical and numerical results derive from an appropriate *for* cycle, that solves the net 317 times, as many as its pipes, and for each of these hydraulic simulations it goes to close in succession one of the pipes.

In Figure 31 and 32, it is reported the summary graph of the Resilience and Failure Index trends deriving from the progressive breaking of the 317 pipelines. Eight pipes were highlighted, positioned in different points of the network (Figure 30):

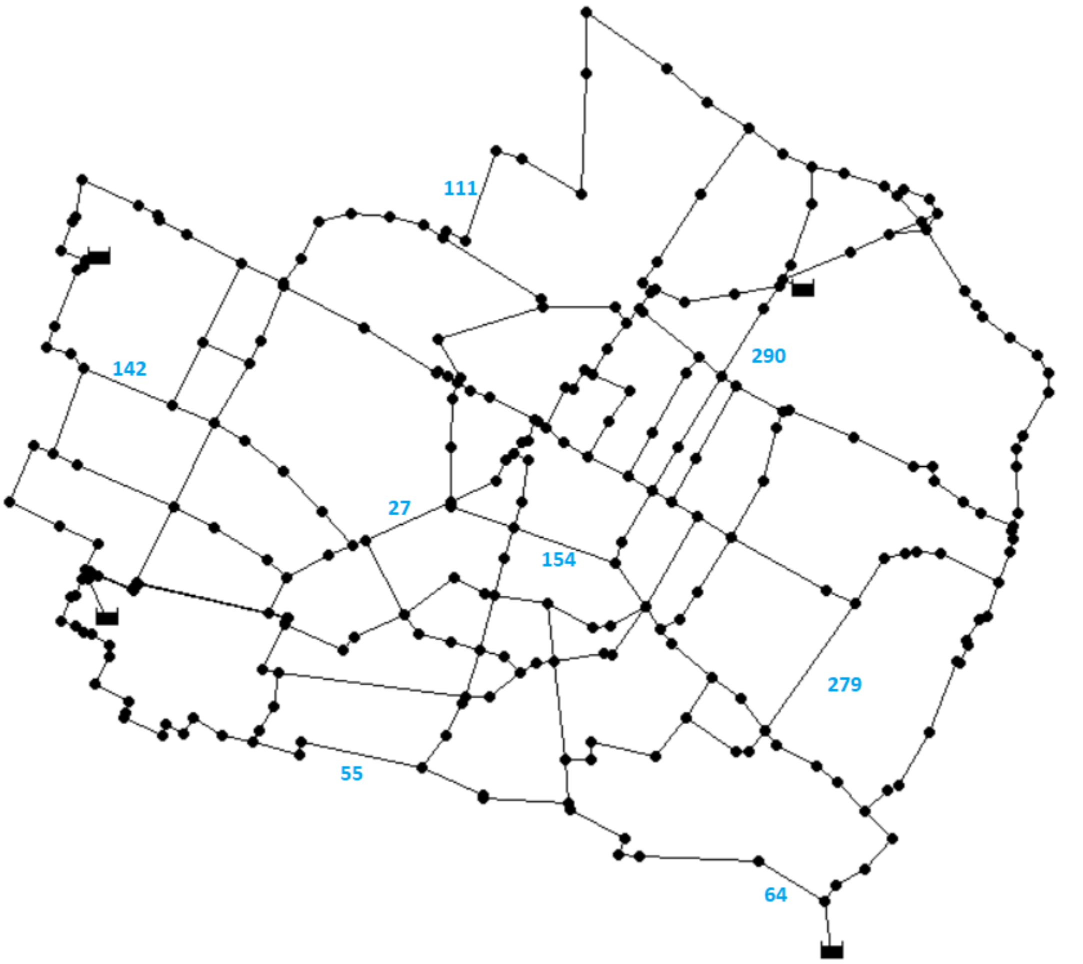


Figure 30 *Modena network with eight underlined pipes*

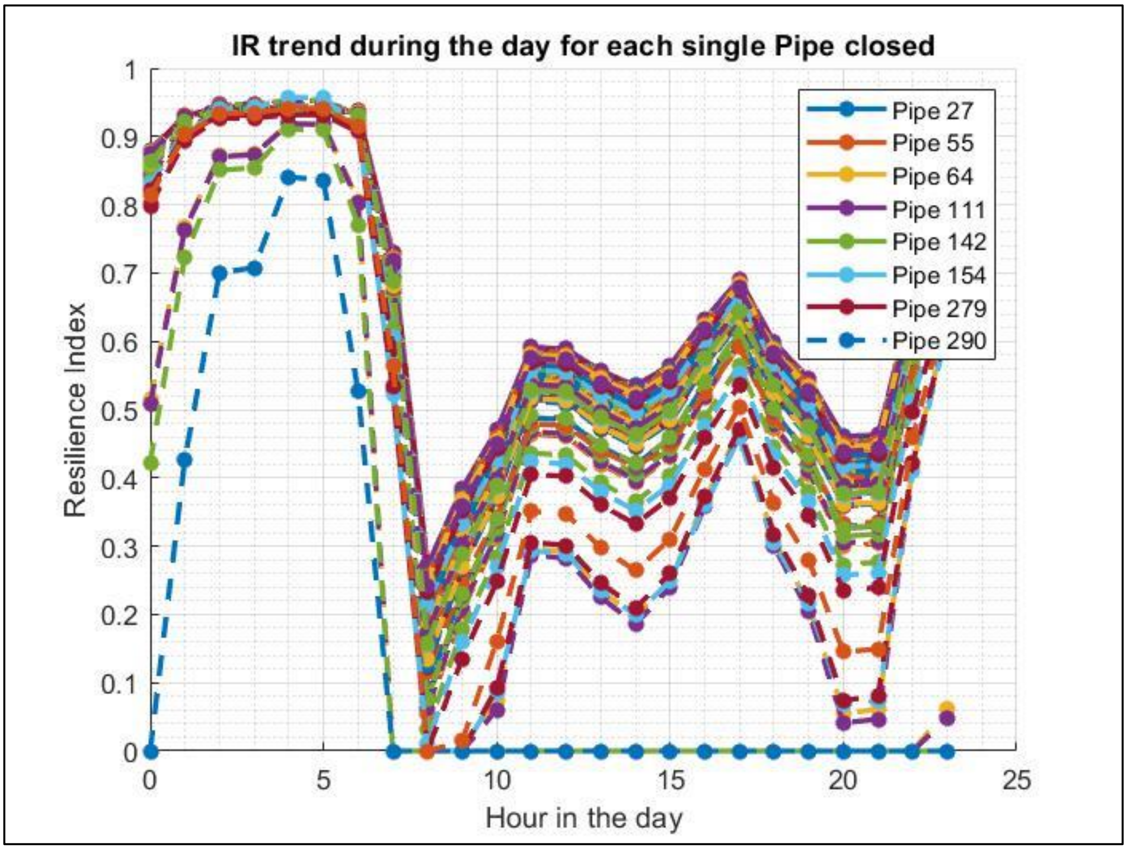


Figure 31 *Trend of the Resilience Index over 24 hours for each pipe closed*

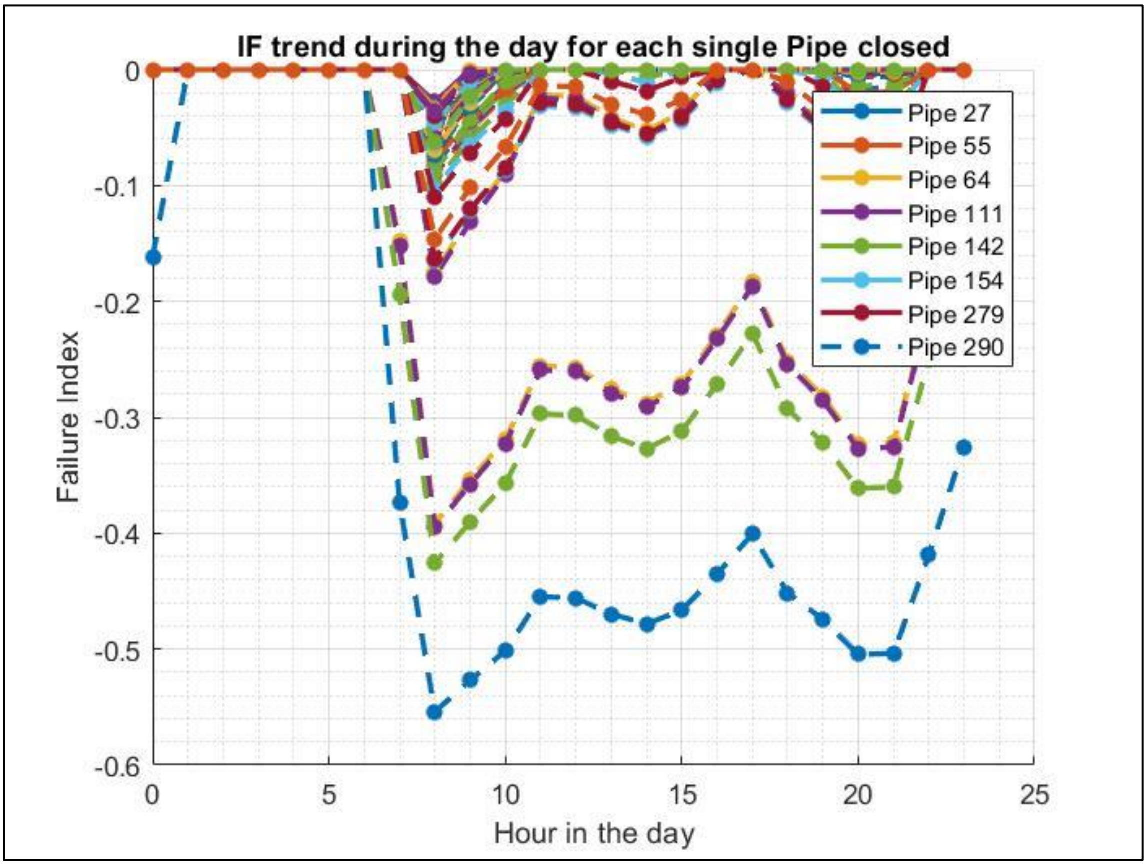


Figure 32 *Trend of the Failure Index over 24 hours for each pipe closed*

Overall, the summary chart shows that the breakdown of each individual pipe causes a lowering of the Resilience Index and an increasing of Failure Index, in particular after the early hours of the morning. Between 5 in the morning and 10 and between 17 and 22 in the evening, the resilience values are subject to a lowering of values, because, when consumption exceeds a certain threshold and when even just one pipe is missing, in some cases, the remaining network is no longer able to restore an acceptable level of resilience.

It is evident that the breakages of the various pipes do not have the same impact on the Resilience Index: the breakage of some pipes is more problematic than others, such as, for example, the failure of pipe 290 would always give negative values after 5 am (Figure 33).

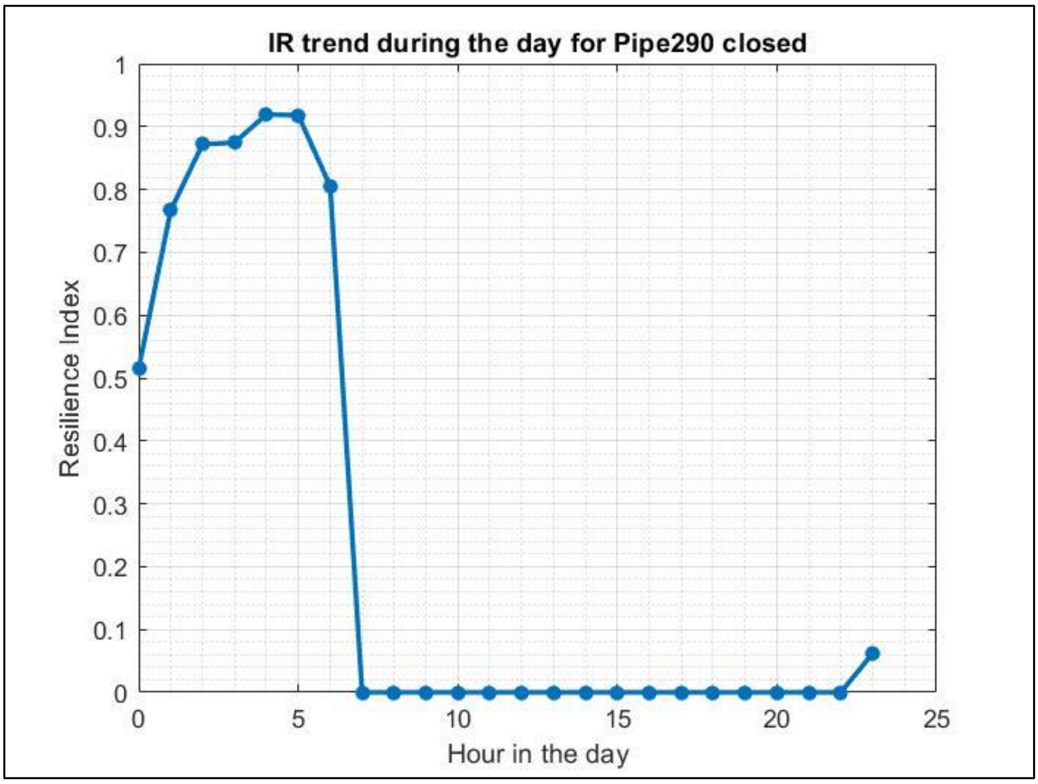


Figure 33 *Trend of the Resilience Index over 24 hours for pipe 290 closed*

Conclusions

The following thesis work summarizes the results obtained from GRA Tool software and from the analysis of the Todini Resilience Index (2000-2016), to define and estimate the performance level of a literature water distribution network, with referring to a failure scenario, the pipe failure.

GRA Tool helped to automate the complex and lengthy process of assessing the resilience of the water distribution system using *GRA*. The main benefits include:

- Allows users to perform comprehensive resilience assessments without knowledge of coding, system failure modeling or water distribution system modeling platform, Epanet. In addition, a detailed understanding of the GRA analysis methodology and scenario development process is not required.
- Key results are automatically extracted, and critical system components can be easily identified on a network map.

In this perspective, having analyzed the scenario linked to the rupture of the pipelines, the final intent of this thesis is to be able to identify the most problematic branches, that is, those that in the event of a failure would cause greater damage to the network, including the lowering of the Resilience Index. In this regard, this analysis can be very useful when planning a pipeline replacement plan or when need to check its integrity, as it allows to understand which pipes to pay more attention to.

In fact, after an initial theoretical framework and after the evaluation of the state of the art of the network, a sensitivity analysis was conducted on resilience, to identify which factors could have the greatest influence on its performance. Based on these studies, interesting considerations have emerged.

First, it was realized that a realistic analysis of the hydraulic performance of a water distribution network, even more so under fault conditions, necessarily requires the adoption of an approach that considers that the flow rate at the nodes is pressure dependent (PDA approach).

In this regard, the results of simulations carried out in Pressure Driven mode, have shown that the variation of the resilience values presents strong correlations with the setting of the pressures at the nodes.

Moreover, thanks to the results obtained, it was possible to ascertain that the network configurations characterized by high values of the Resilience Index result to be more robust towards a possible inefficiency, such as the breaking of a pipe.

In fact, in these cases, the distributions assumed by the Resilience Index values indicate that the higher the resilience, to be intended as the network capacity to absorb the impact of an unforeseen event knowing how to adapt without losing its functionality, the higher is the performance level that the network can supply after the perturbing event.

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