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Vulnerability assessment of water supply infrastructures through multiple indicator methodology

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ABSTRACT

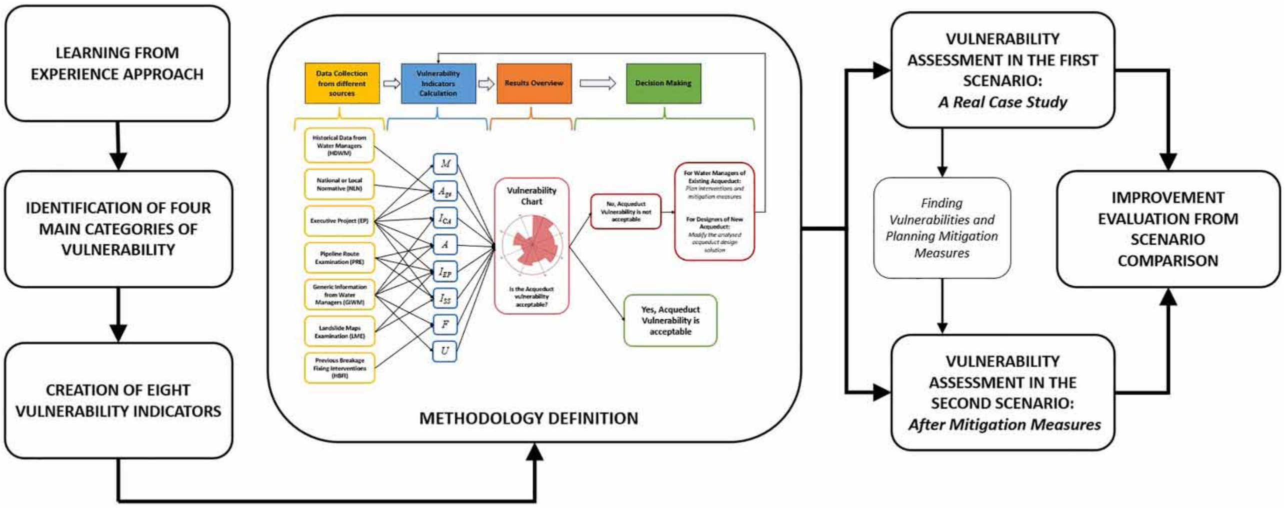
Water supply infrastructures are essential to ensure the well-being of communities and to support social and economic growth and must be protected from damage in the context of future threats related to the environmental consequences of climate change. Those consequences include natural disasters, i.e., landslides, which can cause destruction of water infrastructure, causing distress for water users, cascading effects to other critical infrastructures and environmental impacts. Vulnerability analyses represent a key point in international risk management programs for protecting critical infrastructure, especially in the context of climate change. In this paper, a methodology is proposed to evaluate crucial water supply infrastructure vulnerabilities based on multiple indicators. A learning-from-experience approach is applied to establish specific indicators for vulnerability assessment. Eight different indicators are identified, divided into four categories, regarding land characteristics, service inefficiencies for users due to infrastructure failure, pipeline route characteristics, and physical characteristics of the aqueduct pipe. Along with the indicators, a graphical representation is proposed using the Kiviat chart, producing a vulnerability chart that represents a useful tool to identify the main vulnerability factors in existing water supply infrastructure, in the management of interventions, in the planning and design processes of new infrastructure, and for comparing different design solutions.

Key words: aqueduct vulnerability, critical infrastructure, landslides, multiple indicators, water resources, water supply infrastructure

HIGHLIGHTS

- Vulnerability assessment of water infrastructures using a multiple indicator approach.
- Climate change's side effects on aqueduct breakages due to landslides.
- Water infrastructure management and planning.
- Critical infrastructure vulnerability.
- Vulnerability chart.

GRAPHICAL ABSTRACT



INTRODUCTION

Water infrastructure, such as aqueducts for water supply, represents one of the most important civil infrastructures, guaranteeing freshwater for domestic and industrial uses, and supporting social and economic activities development (Adams 2006).

In the context of climate change, the nature and frequency of natural disasters are bound to increase (Thomas *et al.* 2013), causing potential damage to both the environment and anthropogenic infrastructure. One of the consequences of climate change is represented by landslides (Gariano & Guzzetti 2016; Picarelli *et al.* 2016; Gariano *et al.* 2018; Gariano & Guzzetti 2021), which can affect water supply infrastructure causing damage and service interruptions.

Effects of climate change consequences on water distribution infrastructure represent a topic which deserves to be explored further, as in recent literature this issue has been explored from the perspectives of soil setting changes induced by climate (Wols & van Thienen 2014), changes in moisture and temperature of soils (Kleiner & Rajani 2002), and physical failures of pipeline materials due to seasonal factors (Gould *et al.* 2011).

Important infrastructures in general represent the central core of the economy in all the countries, as they guarantee the possibility to achieve goals of economic and social development and energy sustainability. For the above-mentioned reason, it is essential to ensure the correct operation of important infrastructure mitigating their level of risk and vulnerability. In this regard, recently the European Commission (EC), the United States Department of Homeland Security (USDHS), and others established new rules and guidelines about the security of their country infrastructure because of new international threats. In particular, the EC embraced the green paper 'European Program for Critical Infrastructure Protection' (EC 2005). Afterwards, the Council of the European Union adopted Directive 114/08/EC, 'on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection' (CEU 2008), which led to the European Program for Critical Infrastructure Protection (EPCIP) in 2008. Then, in 2009, the United States (US) promoted the US National Infrastructure Protection Plan (NIPP 2009).

Critical infrastructures in each country are interdependent (Consolini 2009) in that damage or interruption of critical infrastructure in one sector, due to natural disasters, terrorist attacks, or man-made damage, can bring cascading effects on other sectors (Loschel *et al.* 2010). Protecting critical civil infrastructures means defining and implementing a risk management program, including analysis of the vulnerabilities, risk assessment, and implementation of hazard mitigation procedures (Yusta *et al.* 2011).

The term 'vulnerabilities' refers to the weakness level of a system due to failures, disasters, or attacks. Governments, system managers, and regulators agree on directing their attention to evaluating vulnerabilities of national critical infrastructure to accidents or natural disasters (Yusta *et al.* 2011).

Adger (2006) highlighted how the perception of vulnerability issues in literature evolved from the concept of vulnerability to hazards in general, with the identification and prediction of vulnerable groups and critical regions through the likelihood and consequences of hazards (Burton *et al.* 1978, 1993; Parry & Carter 1994; Smith 1996; Anderson & Woodrow 1998); to the concept of vulnerability of coupled human-environment systems, with socio-ecological interactions (Luers *et al.* 2003; Turner *et al.* 2003a, 2003b; O'Brien *et al.* 2004; Luers 2005). Evaluation of vulnerability in civil infrastructure and water-related systems is carried out through different methodologies in literature, from the estimation of specific vulnerability curves (Argyroudis & Mitoulis 2021; Monteleone *et al.* 2022), the establishment of indicator-based methodologies taking into account hydraulic properties and system performances (Hamouda *et al.* 2009; Tabesh & Saber 2012). Water infrastructure is subject to a wide range of risks; damage and operation interruptions that require specific mitigation measures (Baecher 2006) including rapid fixing interventions and management of the emergency. Disasters can cause direct effects, i.e., physical damage to the infrastructure, as well as indirect damages, related to additional expenses for water managers in case of emergencies, as well as the loss of revenue due to the interruption of their services (Gnavi *et al.* 2015).

Referring to methodologies employed to evaluate vulnerabilities in the specific sector of drinking water supply infrastructure, applications are mainly based on rating matrices as well as simulation through system dynamics or multi-agent systems (Lee 2001; Argonne Labs *et al.* 2007, 2008; Quarles & Haimes 2007; Drabble *et al.* 2009). Rating matrices have wide acceptance, especially in risk identification and vulnerability assessment, because the indicators calculated in them are of immediate comprehension. They are also the basis for the generation of hazard maps. In the same way, risk management strategies are based on the generation of decision models that use indicators calculated in rating matrices (Los Alamos Labs & Flaim 2006; Argonne Labs & Peerenboom 2010). Most recent literature on evaluating vulnerabilities of water supply infrastructure examines this issue from different perspectives. The U.S. Environmental Protection Agency evaluated water supply vulnerabilities from the point of view of cybersecurity (Koglin 2017), highlighting how cyber-attacks on water utilities impact public health, not only in the delivery of clean, potable water to consumers but also in other important services that depend on the continuous water supply. Devi *et al.* (2023) analyzed water supply infrastructure vulnerability from a structural perspective, evaluating external influences on soil type and earthquake incidence. Dong *et al.* (2020) analyzed the vulnerability of urban water infrastructure to climate change proposing specific indicators to characterize the sensitivity and adaptive capacity of water-related infrastructures at the city level. Again, at the city level, Wei *et al.* (2022) proposed an approach based on a system dynamics model which includes the relationship between socio-economic development and water resources sustainable utilization for the case study of the Pearl River Delta.

There are different indicators in the literature for vulnerability assessments depending on study goals and targets (Hinkel 2011). Indicators can be selected using different criteria. For example, through a deductive approach based on a framework (Robielos *et al.* 2020; El-Maissi *et al.* 2022), theories, or physical relationships; through an inductive approach based on statistics, and through an approach based on normative or only on data (Hinkel 2011; Adger *et al.* 2004). Approaches can also be hybrid; i.e., a combination of the above-mentioned ones or not clearly belong to any of them, rather being based on specific characteristics of the analyzed infrastructures (Hinkel 2011; Adger *et al.* 2004; Hamouda *et al.* 2009; Heink & Kowarik 2010; Gain *et al.* 2012; Anandhi 2017).

Input data for vulnerability analyses of water supply infrastructure can be stochastic data or deterministic data. In the case of stochastic data, such as climatic variables or hydrological time series, a pre-processing step is necessary to understand the statistical characteristics of the data (Burgan *et al.* 2017; Chebana & Ouarda 2021). In the case of deterministic data, such as information directly collected from water managers, executive projects, and local or national normative, an in-depth study for the scientist or generally for the vulnerability analysis performer is recommended.

In this study, a methodology is proposed to evaluate crucial drinking water infrastructure vulnerabilities to natural hazards with a specific emphasis on landslides. The need for this study arises from real events that occurred in the Messina area (Italy) in October 2015 when, due to a landslide, the main aqueduct of the city, the Fiumefreddo aqueduct, broke down. Practical difficulties in fixing the aqueduct pipe had left Messina City without a drinking water supply for almost a month, causing a 'national emergency' situation. Recent studies support the relationship between landslides and climate changes (Picarelli *et al.* 2016; Gariano & Guzzetti 2021), and specifically in southern Italy (Gariano *et al.* 2015; Picarelli *et al.* 2016), the area of the case study here analyzed.

A learning-from-experience approach is applied in this study to establish a methodology for vulnerability assessment, and for the definition of specific indicators, arising from real issues faced in the October 2015 break event. Four main categories of vulnerability indicators are identified, namely, land characteristics, service inefficiencies for users due to infrastructure failure, pipeline route characteristics, and physical characteristics of the aqueduct pipe. All indicators proposed here were developed by the author as such specific indicators for aqueduct vulnerability assessment are not available in the literature. To develop such indicators and to establish a methodology for the purpose of an approach that learns from experiences, a detailed examination of issues faced in the October 2015 breakage event has been carried out, highlighting specific aspects of vulnerability and indirect damages to aqueduct infrastructures.

The new vulnerability indices developed in this study by the author, and the application of the above-mentioned indices for the first time to an existing case study, which has faced serious issues in the past, represent the novelty of this study. The proposed methodology aims to serve as a valid instrument both for vulnerability assessment of existing aqueducts, and as a support tool in evaluating pipeline routes during planning phases of aqueduct infrastructure design, right before construction.

Assessing vulnerability with the multiple indicator methodology presented here can represent a valid and simple instrument to evaluate and compare different designs or revamping solutions in pipeline route planning for new infrastructures. Different scenarios can be easily assessed, evaluating the merits and weaknesses of every solution in terms of infrastructure vulnerability, and supporting engineers and water managers in decision-making processes.

METHODS

This section contains first a description of the case study of the Fiumefreddo aqueduct, the main water resources supplier of Messina City, and of its breakage event in October 2015. Then, the proposed methodology for vulnerability assessment is described and all specific vulnerability indicators are illustrated.

Case study description

The Fiumefreddo aqueduct is the main hydraulic infrastructure serving the city of Messina (Italy) (Borzì 2022). It takes water from the Etna Mountain groundwater aquifer bringing 1,000 l/s from the Calatabiano area to Messina city center through a complex pipe route of 65 km in length (Figure 1). Messina City (Italy) has around 250,000 inhabitants and previous studies highlighted how, even if other minor water sources exist, its water distribution system is largely dependent on the main supply of the Fiumefreddo aqueduct (Borzì *et al.* 2019, 2020; Borzì & Bonaccorso 2021).

Fiumefreddo aqueduct was built between 1984 and 1987; its pipe is made of steel, with a diameter of NPS1000 (Nominal Pipe Size 1 m). The pipeline route is full of special structures: street crossings and railway crossings, four big tunnels in the locations of Taormina, Forza D'Agrò, and two in Scaletta, with lengths, respectively, of 1,471, 951, 139, and 291 m. There are also more than 100 watercourse crossings, divided into tube-bridge ones and under-riverbed ones. Due to its route and the complexity of its territory, it is at high risk of breakage, counting more than 10 extraordinary repair interventions during the years in different locations, which left Messina City without a water supply for days.

The most significant breakage event happened in October 2015, when due to a landslide the aqueduct's pipe broke down in the Calatabiano (CT) location (Figure 2). Because of local terrain characteristics, climatic conditions, and landslide extent, it

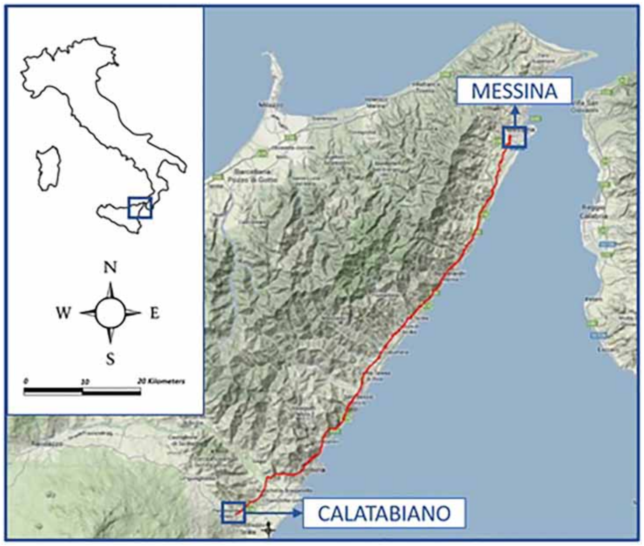


Figure 1 | Case study location (in Italy). Fiumefreddo aqueduct pipeline route on the map (in red).

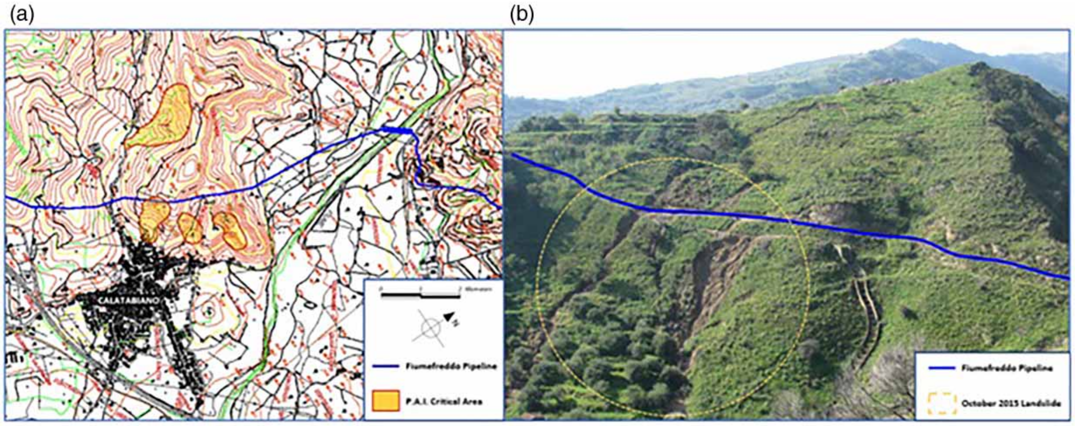


Figure 2 | (a) Pipeline route of Fiumefreddo aqueduct close to Calatabiano highlighting some landslide-critical areas reported by Basin Plan. (b) Picture of the landslide that caused the pipeline breakage in October 2015. In this picture, the pipeline route is highlighted in blue and landslide terrains are visible.

was very difficult to access the break site with mechanical devices to allow the repair of the pipeline. The consequence of practical difficulties in fixing the aqueduct pipe was that Messina City was left without sufficient drinking water supply for almost a month, causing a 'national emergency' situation and great distress to water users and other infrastructure.

Figure 2(a) shows the pipeline route of the Fiumefreddo aqueduct, close to Calatabiano, in the area where the October 2015 breakage event happened. This figure also highlighted some landslide-critical areas reported by the Basin Plan for Flood and Landslide Risk of Sicilian Region (P.A.I. – Piano Stralcio di Bacino per l'Assetto Idrogeologico, in Italian) (Regione Sicilia 2006). In this plan, the landslide-affected areas are categorized into four risk classes, i.e., low, medium, high, and very high. Figure 2(b) is a picture of the landslide that caused the pipeline breakage in October 2015. In this picture, the pipeline route is highlighted in blue and landslide areas are clearly visible. As it is possible to deduce from the picture, the area where the pipeline route is located was very difficult to reach by site vehicles in order to rapidly repair the breakage, and the landslide is quite extensive.

The October 2015 breakage event and its consequent impacts on Messina City highlighted the necessity of an in-depth study on the Fiumefreddo aqueduct vulnerability and the importance of this critical infrastructure.

The proposed methodology for vulnerability assessment

The present proposed methodology for vulnerability assessment is based on four main steps, as shown in the flowchart in Figure 3. The first step is (1) collecting data from different sources. In this phase, an in-depth analysis of the pipe route is necessary to focus on some critical characteristics of the infrastructure, such as the presence of special structures or complex rivers, railways, and street crossings. At the same time, in this step, it is necessary to identify on the map critical areas that could be influenced by landslides or other natural hazards. The second step (2) is to apply vulnerability indicators proposed in this study, and the third step (3) is to prepare a vulnerability chart for the analyzed aqueduct infrastructure, which allows an overview of results in terms of vulnerability. Then, the last step (4) involves decision-makers: here, they can consider the vulnerability of the aqueduct previously evaluated as acceptable or not acceptable. In the case decision-makers are water managers of an existing aqueduct. If they find the vulnerability of their aqueduct to be unacceptable, they can plan interventions and mitigation measures and go back to the second step of the methodology calculating new vulnerability indicators. In the same way, in the case of new aqueducts in a planning phase, designers who find the vulnerability of their design solution to be unacceptable can modify their design solution and calculate vulnerability indicators for the new one.

Vulnerability indicators

Four different categories of vulnerability indicators are proposed, with a total of eight different indicators (Table 1). In the vulnerability assessment using multiple indicators, proper normalization and aggregation of vulnerability indicators are essential (Böhringer & Jochem 2007). Normalization, in particular, is important to make data comparable and easy to understand, to avoid disproportionalities while combining multiple indicators (Ebert & Welsch 2004). All vulnerability indicators are

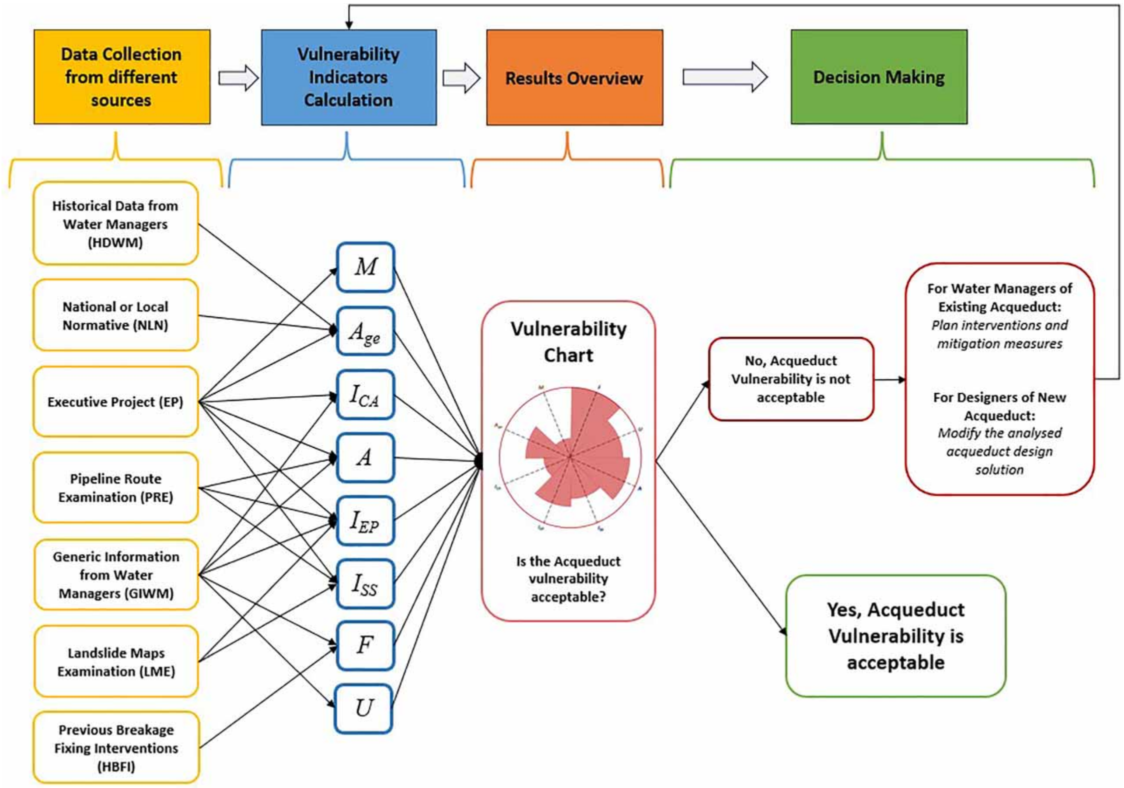


Figure 3 | Flowchart of the proposed methodology.

Table 1 | Vulnerability indicators

Category	Vulnerability indicator name	Symbol
Physical characteristics of the pipe	Material Index Aging Index	M A_{ge}
Lands and terrain characteristics	Corrosion Exposure Index by Aquifer Exposure Index of the Pipe to Landslides	I_{CA} I_{EP}
Service inefficiencies for users	Index of Service Failure Uniqueness Index	F U
Pipeline route	Accessibility Index Exposure Index of Special Structures to Landslides	A I_{SS}

normalized assuming values between 0 and 1, where 0 means infrastructure is not vulnerable at all, and 1 means infrastructure is highly vulnerable. To make information on vulnerability assessment easily understandable and comparable, vulnerability indicators can be classified as reported in Table 2. Vulnerability indicators assuming values between 0 and

Table 2 | Vulnerability indices range and definition

Vulnerability index range	Description
0–0.3	Low vulnerability
0.3–0.6	Medium vulnerability
0.6–1	High vulnerability

0.3 represent ‘low vulnerability’, the ones assuming values between 0.3 and 0.6 represent ‘medium vulnerability’ and the ones assuming values between 0.6 and 1 represent ‘high vulnerability’ of the infrastructure.

The first category of vulnerability indicators here proposed regards the physical characteristics of the pipe (PCP). The characteristics of materials influence the durability and reliability of every infrastructure, and they are affected by time. In this category, it is possible to identify two indicators: the Material Index (M) and the Aging Index (A_{ge}).

The second category regards lands and terrain characteristics, as geological and hydrogeological characteristics of terrains can directly affect aqueduct pipes in case of the presence of an aquifer, which can cause corrosion to the pipe, or landslides that can cause breakages. In this category, it is possible to identify two indicators: the Corrosion Exposure Index by Aquifer (I_{CA}) and the Exposure Index of the Pipe to Landslides (I_{EP}).

The third category considers service inefficiencies for users due to infrastructure failures. In this category, indicators can also assume the meaning of indirect damage indicators as they are strictly connected with users’ discomforts which indirectly leads to other cascading issues. In this category, it is possible to define the Index of Service Failure (F) and Uniqueness Index (U).

The fourth category refers to pipeline route characteristics, as it is a fundamental element in aqueduct vulnerability assessment. In this category, it is possible to identify the Accessibility Index (A) and the Exposure Index of Special Structures to Landslides (I_{SS}).

The Material Index was determined from the literature (Kettler & Goulter 2011; Rezaei *et al.* 2015; Samba *et al.* 2016) and technical reports on the aqueduct’s ordinary breakage and maintenance records evaluations, producing a reference table (Table 3) for most common materials of aqueduct pipes and differencing M value in case of presence or absence of cathodic protection in the aqueduct. Steel and cast iron results have a low vulnerability M index in the case of cathodic protection of 0.15 and 0.30, respectively. Those two materials are very strong and ductile, and can deform without breaking if exposed to slight stresses. For those materials, the case of missing cathodic protection increases vulnerability to high values (0.50 for steel and 0.80 for cast iron), as ordinary maintenance in steel and cast iron pipelines often sees damage without cathodic protection. For concrete, prestressed concrete, PVC (polyvinyl chloride), PE-HD (high density polyethylene), and GFRP (glass fiber reinforced polymer) materials, cathodic protection does not influence vulnerability, as they are non-conducting materials. Concrete and prestressed concrete are strong in compression but not ductile, as they are brittle and fracture under pressure. For this reason, their values of M are, respectively, 0.55 and 0.45 for concrete and prestressed concrete. Plastic materials, like PVC, PE-HD, and GFRP, are not very strong, they can easily deform under pressure and break, and their M values are 0.85, 0.70, and 0.80, respectively.

The Aging Index (A_{ge}) is defined as:

$$A_{ge} = \begin{cases} \dfrac{A_e}{A_p}, & A_e < A_p \\ 1, & A_e \geq A_p \end{cases} \tag{1}$$

where A_e represents the age of the aqueduct, i.e., the number of years of operation, and A_p represents the design life year for which the aqueduct has been planned. The design life age of important infrastructure like an aqueduct can vary from country to country and can change with the introduction of new regulations. Generally, a huge and expensive infrastructure is kept in

Table 3 | Values for Material Index (*M*) vulnerability indicator

Pipe material	*M* with cathodic protection	*M* without cathodic protection
Steel iron	0.15	0.50
Cast iron	0.30	0.80
Concrete	0.55	0.55
Prestressed concrete	0.45	0.45
PVC	0.85	0.85
PE-HD	0.70	0.70
GFRP	0.80	0.80

operation for longer periods than its design life age, and this can cause an increase in vulnerability due to material durations. For this reason, the Aging Index increases proportionally with the age of the aqueduct A_e and reaches its maximum value of 1 when A_e is equal to or greater than the design life A_p.

The Corrosion Exposure Index by Aquifer (I_{CA}) is defined as:

$$I_{CA} = \frac{\sum_{j=1}^{L/100} t_j}{j} \tag{2}$$

$$t_j = \begin{cases} 1, & \text{if the } j\text{th segment of the aqueduct intersects an aquifer} \\ 0, & \text{if the } j\text{th segment of the aqueduct does not intersect an aquifer} \end{cases} \tag{3}$$

To evaluate I_{CA}, the aqueduct pipeline route has to be firstly discretized in j segments. The value of j depends on the lengths of the aqueduct in meters L, as shown in Table 4. After defining the number of aqueduct segments for this indicator calculation, it is necessary to verify if for each of the defined segments, there is an intersection with local aquifers and if in each jth part, the aqueduct intersects them. For this purpose, each jth part of the aqueduct is associated with a binary variable t_j which can assume the value of 1, if the jth segment of the aqueduct pipe intersects an aquifer, otherwise the value of 0 if the jth segment of the aqueduct does not intersect an aquifer (Equation (3)). The I_{CA} indicator is finally evaluated using Equation (2). This indicator gives information on how much of the aqueduct length is affected by the presence of an aquifer, the presence of which can have consequences in terms of corrosion. If the I_{CA} value is equal to 0, it means that there is no aquifer affecting any part of the entire aqueduct pipeline route, consequently, vulnerability for corrosion by the aquifer would be null.

For evaluating the Exposure Index of the Pipe to Landslides (I_{EP}), it is first necessary to analyze the pipeline route of the aqueduct and highlight wherever it is intersected by the presence of a landslide.

The I_{EP} index is defined as:

$$I_{EP} = \begin{cases} 1 - \dfrac{d_{PLm}}{100D}, & d_{PLi} < 100D \\ 0, & d_{PLi} \geq 100D \end{cases} \tag{4}$$

$$d_{PLm} = \frac{\sum_{i=1}^{n} d_{PLi}}{n} \tag{5}$$

where D represents the diameter of the pipe in meters, d_{PL} represents the distance in meters between each landslide face and pipeline, taken orthogonally to the pipe axis, and i represents the ith segment of the aqueduct interested by a landslide. With Equation (5), it is possible to evaluate a mean value of d_{PL}, where n represents the number of landslides interesting the entire aqueduct, and then with Equation (4), it is possible to evaluate I_{EP} which assumes values between 0 and 1 when d_{PLi} assumes values less than $100D$, and 1 in the other cases.

The Index of Service Failure (F) is defined as:

$$F = \begin{cases} \dfrac{T_{FIX}}{T_{ES}}, & T_{FIX} < T_{ES} \\ 1, & T_{FIX} \geq T_{ES} \end{cases} \tag{6}$$

Table 4 | Number of pipeline route segments j for Corrosion Exposure Index by Aquifer (I_{CA}) calculation depending on aqueduct length L

j	L (meters)
5	$L \leq 3{,}000$
10	$3{,}000 < L \leq 5{,}000$
20	$5{,}000 < L \leq 10{,}000$
50	$10{,}000 < L \leq 30{,}000$
100	$30{,}000 < L \leq 50{,}000$
130	$L > 50{,}000$

where T_{FIX} represents the mean fault repair time in hours, obtained from historical data of previous breakage fixing interventions; and T_{ES} represents the water resource depletion time in the city supplied by the aqueduct, in hours. It is relevant to know T_{ES} because it gives quantitative information about the time period in which the city supplied by the analyzed infrastructure does not experience the effects of pipeline breakage or malfunctions causing an interruption in water supply. T_{ES} value is directly associated with water supply system characteristics and can be evaluated from information on urban tank capacities or from historical usage data of previous maintenance interventions.

The Uniqueness Index (U) is defined as:

$$U = \frac{Q_A}{Q_{TOT}} \tag{7}$$

where Q_A represents the mean annual flow in m^3/s of the analyzed aqueduct and Q_{TOT} represents the mean annual flow in m^3/s, provided to the city/cities supplied by the analyzed aqueduct, from all available sources. This indicator provides information on how 'unique' the analyzed infrastructure is for the city supplied. If the analyzed aqueduct is the only source of supply, the U indicator assumes the value of 1 indicating a high level of vulnerability.

The Accessibility Index (A) is defined as:

$$A = \begin{cases} \dfrac{d_{Am}}{100\,D}, & d_{Am} < 100\,D \\ 1, & d_{Am} \geq 100\,D \end{cases} \tag{8}$$

$$d_{Am} = \frac{\sum_{k=1}^{v} d_{Ak}}{v} \tag{9}$$

where D is the diameter of the pipe in meters, d_A is the distance in meters, evaluated orthogonally to the pipe axis, between the pipeline and the closest 'accessible point', defined as an infrastructure accessible with mechanical vehicles, k represents the kth segment of the aqueduct with an accessible infrastructure close by, and v represents the number of accessible points. With Equation (9), it is possible to evaluate a mean value of d_A, and then, it is possible to evaluate A which assumes values between 0 and 1 when d_{Ak} assumes values less than $100D$, and 1 for other cases.

The Exposure Index of Special Structures to Landslides (I_{SS}) is defined as:

$$I_{SS} = \begin{cases} 1 - \dfrac{d_{SLm}}{100D}, & d_{SLi} < 100D \\ 0, & d_{SLi} \geq 100D \end{cases} \tag{10}$$

$$d_{SLm} = \frac{\sum_{i=1}^{n} d_{SLi}}{n} \tag{11}$$

where D represents the diameter of the pipe in meters, d_{SL} represents the distance in meters between each landslide face and the special structure of the pipeline, taken orthogonally to the pipe axis. With Equation (11), it is possible to evaluate a mean value of d_{SL}, and then, it is possible to evaluate I_{SS}, which assumes values between 0 and 1 when d_{SLi} assuming values less than $100D$, and 1 for other cases.

For the evaluation of the eight vulnerability indicators described above, it is necessary to collect information regarding characteristics of the analyzed infrastructure, such as diameter of the aqueduct pipe, aqueduct flow, length of the pipeline, age of the aqueduct, design life of the aqueduct, total amount of water supply provided to the city by the analyzed aqueduct, the water resource depletion time in the city supplied by the aqueduct, historical information on previous breakage events and on their repair time, and so on.

All this information can be collected from different sources, such as the executive project (EP) of the aqueduct, historical data from water managers (HDWM), national or local normative (NLN), pipeline route examination (PRE), landslide maps examination (LME), historical data of previous breakage fixing interventions (HBFI), and generic information from water managers (GIWM). Table 5 lists all the parameters needed to evaluate each of the eight vulnerability indicators, with a brief description, information on measurement units, boundary conditions, source of information, and some specific notes.

RESULTS AND DISCUSSION

Two scenario configurations are analyzed here. The first scenario considers the vulnerability analysis of the Fiumefreddo aqueduct in its actual configuration. After evaluating the existing vulnerability of the Fiumefreddo aqueduct and identifying its critical aspects, a second scenario is defined considering some specific interventions (for example, land reinforcements, changes in the pipeline route, diversification in water supply, and so on) able to limit the effects of those causes which makes this infrastructure more vulnerable, and for this configuration, vulnerability indicators are again evaluated.

Table 5 | Parameters for vulnerability indicators evaluation

Variable	Unit	Description	Minimum value	Maximum value	Source	Details
A_e	Years	Age of the aqueduct	0	A_p*	EP/HDWM/NLN	*In case $A_e > A_p$, $A_{ge} = 1$
A_p	Years	Design life of the aqueduct	30*	50*	EP/HDWM	*Depending on LNL
L	m	Length of the aqueduct	100*	Any length	EP/GIWM	*Aqueducts shorter than 100 m in length are usually not primary infrastructures
j	No unit	Number of pipeline parts for I_{CA} evaluation	1	$L/100$	EP/GIWM	
D	m	Diameter of the pipe	0.1*	Any diameter	EP/GIWM	*Aqueducts smaller than 0.1 m in diameter are usually not primary infrastructures
d_{PL}	m	Distance between each landslide face and the pipe*	0	$100D$	PRE/LME	*Taken orthogonally to the pipeline axis
i	No unit	ith segment of the pipe affected by landslide	0	n*	PRE/LME	*Depending on the number of landslides affecting pipeline route
T_{FIX}	h	Mean fault repair time	0	Any value	HBFI	
T_{ES}	h	Water resource depletion time*	0	Any value	GIWM	*In the city supplied by the analyzed aqueduct
Q_A	m^3/s	Aqueduct flow	0	Q_{TOT}	GIWM	
Q_{TOT}	m^3/s	Total amount of water supply from all sources*	0	Any value	GIWM	*In the city supplied by the analyzed aqueduct
d_A	m	Distance between the pipe and the closest infrastructure*	0	$100/D$	PRE	*Taken orthogonally to the pipeline axis
k	No unit	kth segment of the aqueduct with an accessible infrastructure close by	0	v*	EP/PRE	*Depending on the number of accessible points
d_{SL}	m	Distance between each landslide face and the special structure of the pipeline*	0	$100D$	PRE/LME	*Taken orthogonally to the pipeline axis

For each line, the symbol '*' is a reference to the 'Details' column.

Vulnerability assessment in the first scenario: the actual configuration

In this first scenario, the methodology for vulnerability assessment above described is applied at the Fiumefreddo aqueduct in its actual configuration.

Firstly, the pipeline route of the Fiumefreddo aqueduct has been analyzed in-depth highlighting more than 100 river crossings, 4 big tunnels, a route full of special structures, railways and street crossings, and evidencing hundreds of critical areas due to landslides in the proximity of the pipeline route with different hazard levels. In the design of an aqueduct, defining the best route for the pipelines is a critical issue because it allows transferring water resources from supply sources to city tanks and it must be chosen appropriately, combining technical aspects with economic ones. It is, therefore, essential to know the geological, geotechnical, and topographic characteristics of the terrains along the route, their stability, and the presence of both surface and groundwater. The choice of the route, as well as the materials to be adopted, are strongly influenced by the above-mentioned factors. Hundreds of critical areas have been identified along the Fiumefreddo pipeline route due to landslides with different hazard levels according to Basin Plan classification. Around 100 landslide areas classified by Basin Plan with a high and very high hazard level indication have been selected and used for vulnerability indicators computation (Regione Sicilia 2006). For example, Table 6 describes some landslides with very high hazard levels which are relevant to the Fiumefreddo pipeline route, with Basin Plan critical area code, landslide type classification, and information on the localization.

Information on the physical characteristics of the aqueduct pipe, on aqueduct flow, and on previous breakage events, including that of October 2015, on fixing time has been collected from the EP of the aqueduct and historical information from water managers.

Information on the total amount of water supply available for Messina City has also been collected from water managers and is available in literature (Borzì *et al.* 2019, 2020; Borzì & Bonaccorso 2021; Borzì 2022). In particular, Messina City is mainly supplied by Fiumefreddo aqueduct, providing 1 m^3/s water supply and secondly from Santissima Aqueduct providing 0.15 m^3/s (Borzì & Bonaccorso 2021; Borzì 2022). All this information has been used for the evaluation of vulnerability indicators described in previous sections, for the actual configuration in this first scenario.

The eight vulnerability indicators are then evaluated. Their values are reported in Table 7, and in Figure 4, the vulnerability chart is represented with the Kiviat chart, to combine multi-indicator information.

Values of vulnerability indicators provide information on specific vulnerabilities of the Fiumefreddo aqueduct. The lowest degrees of vulnerability in the comparison between all indicators are represented by the Material Index (M), with a low/medium value of vulnerability (0.3). This result is confirmed by some practical evidence about this specific case study that, from technical reports on pipeline maintenance status highlights, in some pipeline portions, a deformation occurred instead of breakage under pressures or small landslides and terrain movements. The characteristics of ductile materials like steel iron are to plasticize under pressure avoiding fragile breaking, and guaranteeing good resistance.

The Corrosion Exposure Index by Aquifer (I_{CA}) assumes a medium value of vulnerability (0.35). This result is confirmed by the fact that historical information on pipeline maintenance status does not report significant damages to the pipe that can be attributed to aquifer corrosion exposure.

Table 6 | Example of Basin Plan classified landslide areas with very high hazard levels along the Fiumefreddo pipeline route

Catchment area	City	District	Critical area code	Landslide type
Alcantara	Catania	Calatabiano	096-3CL-001	Complex landslides
			096-3CL-002	Collapse or overturn
			096-3CL-012	Sliding
			096-3CL-013	Diffuse landslides
Alcantara/Fiumara D'agrò	Messina	Taormina	097-5TA-030	Diffuse landslides
		Taormina	097-5TA-041	Landslides for intense erosion processes
		Letojanni	097-5LT-004	Collapse or overturn
Fiumedinisi – Capo Peloro	Messina	Alì Terme	102-5AT-012	Collapse or overturn
		Scaletta Zanclea	102-5ZS-017	Collapse or overturn

From the hundreds of landslides highlighted by Basin Plan, the nine critical areas are reported in this table with very high hazard classification that are closest to pipeline.

Table 7 | First scenario: Vulnerability indicator values for Fiumefreddo aqueduct in the actual configuration

Indicator	Value	Vulnerability
M	0.3	Low/Medium
A_{ge}	0.58	Medium
I_{CA}	0.35	Medium
I_{EP}	0.73	High
F	1	High
U	0.83	High
A	0.89	High
I_{SS}	0.61	High

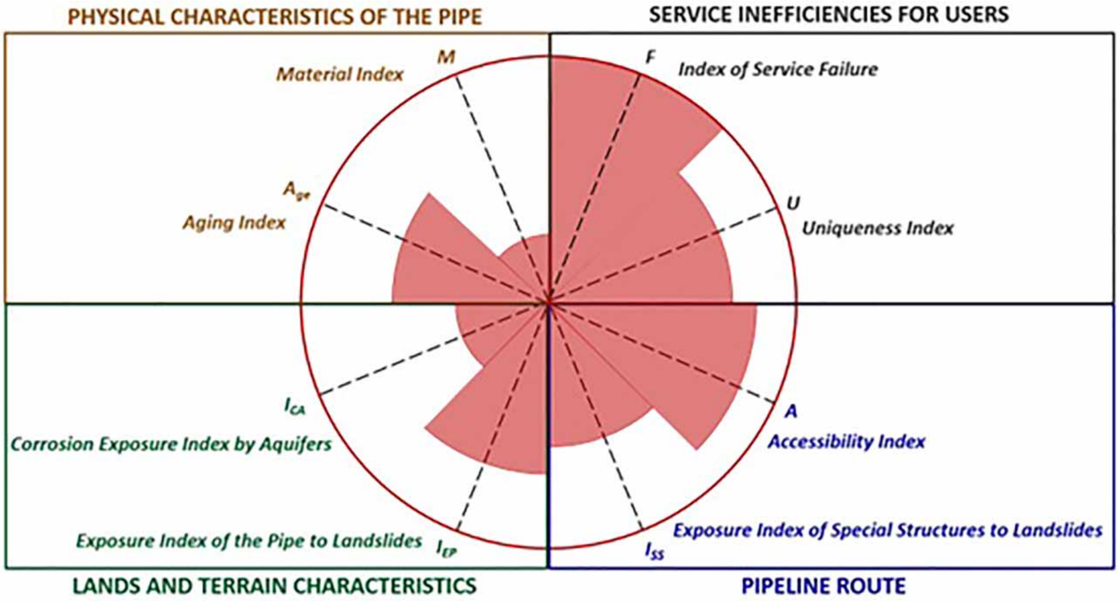


Figure 4 | First scenario: Vulnerability chart for Fiumefreddo aqueduct in its actual configuration. The eight indicators are reported and named in the vulnerability chart, classified by categories.

The Aging Index (A_{ge}) assumes a value of 0.58, which suggests that the Fiumefreddo aqueduct has not yet reached its design life age but should be checked in the future years.

The Exposure Index of the Pipe (I_{EP}) and of Special Structures (I_{SS}) to Landslides assumes values of 0.73 and 0.61, respectively, corresponding to a high vulnerability for the Fiumefreddo aqueduct from this perspective. This is corroborated by historical information on pipe breakage, caused in most of the cases by landslides.

The Accessibility Index (A) assumes a value of 0.89, corresponding to high vulnerability. An in-depth analysis of the pipeline route shows that the latter, along its 65 km length, goes through many areas far away from streets accessible by mechanical vehicles, and this was also confirmed from the facts of October 2015, when the difficulties in accessing the pipe breakage point area caused many issues in terms of time and distress to water users.

The Uniqueness Index (U) assumes a value of 0.83, corresponding to a high value of vulnerability. This is confirmed both by the mere fact that Fiumefreddo aqueduct is the main source of water supply for Messina City, and again by the October 2015 breakage event, when the interruption in Fiumefreddo aqueduct water supply caused a high level of distress for water users who spent almost a month without sufficient water supply.

Finally, the Index of Service Failure (F) assumes the value of 1. From historical information computed including fixing time spent in the October 2015 breakage event, this indicator assumes the highest value of vulnerability in the whole analysis for the Fiumefreddo aqueduct.

The latter (F), combined with the other indicators with the highest values of vulnerability (U and A), gives information on the most vulnerable aspects of this specific infrastructure. Those three indicators can be interpreted also as indirect damage indicators. Because of their high values of vulnerability, water users are severely affected by water crises and distress during infrastructure failure.

Vulnerability assessment in the second scenario: after mitigation measures

In the second scenario, the methodology for vulnerability assessment described above is applied at the Fiumefreddo aqueduct in its configuration after mitigation measures.

Firstly, the results of the first scenario analysis are examined using vulnerability indicator values to understand which specific aspect to focus mitigation interventions to decrease the vulnerability of the aqueduct infrastructure. This approach in vulnerability assessment of water infrastructure, in the context of vulnerability assessment of water resources, is considered a powerful analytical tool for describing states of risk, powerlessness, and the marginality of systems, and for guiding actions to enhance prosperity through mitigation of risk against natural hazards (Adger 2006).

The proposed approach shows where unsustainability may be most likely in a specific water infrastructure, an issue considered relevant in literature (Bär *et al.* 2015). This kind of assessment can provide decision-makers with simple and easy-to-understand parameters to identify priority needs and justify their actions, as highlighted by Harley *et al.* (2008).

Providing planners with insights on focus areas to reduce the system's vulnerability is one of the applications of the proposed methodology, as evidenced in the literature (Hamouda *et al.* 2009). Evaluating new planning solutions in water resources management, as well as to evaluate, modify, and improve existing ones is also a relevant issue (Babel *et al.* 2011; UNEP 2011) finding in the proposed methodology a valid and easy application tool.

In planning extraordinary maintenance interventions, the vulnerability chart gives a precious indication of aspects of infrastructure vulnerability that should be prioritized. In this specific case, the high value of the Uniqueness Index ($U = 0.83$, see Table 7) tells water managers that it should be useful to differentiate water sources for Messina City, to make the system more flexible and less vulnerable in case one of the aqueduct infrastructures serving the city breaks. Recent literature information (Borzì 2022), and data from water managers, show that Messina City can have the possibility to differentiate its water supply sources, by taking water from Alcantara Aqueduct for 0.3 m^3/s and from multiple small urban wells for 0.22 m^3/s, in addition to the actual configuration that sees water supply from Fiumefreddo aqueduct, providing 1 m^3/s and from Santissima Aqueduct providing 0.15 m^3/s.

The Index of Service Failure (F) value, given by the ratio between the mean fault repair time, obtained from historical data of previous breakage repair interventions, and the water resource depletion time in the city, tells water managers that it would be useful to improve urban tank capacities to increase the time period in which the city does not perceive the effects of pipeline breakage or malfunctions causing interruption in water supply. Information from water managers shows the possibility for Messina City's water distribution system to improve its city-wide tank capacities by introducing a new main tank called 'Montesanto 1', which with its capacity improves the urban water availability in case of aqueduct breakages.

The high level of Exposure Index of the Pipe (I_{EP}) and of Special Structures (I_{SS}) to Landslides indicates that planning to make modifications to pipeline routes or bypass to overcross landslide-critical areas can improve the reliability of the aqueduct by decreasing vulnerability to landslides. To mitigate those vulnerabilities, in this scenario some measures are proposed (Table 8).

Regarding special structures exposed to terrains affected by landslides, proposed here is a landslide mitigation measure focused on the land reinforcement type of intervention. This kind of intervention affects 6 river crossings, 11 street crossings, 4 tunnels, and 3 railway crossings, for a total length of the pipeline interested by modification of 355, 1,377, 2,852, and 446 m, respectively. For portions of the pipeline route exposed to landslides, it is proposed to bypass landslides by modifying the pipeline route in those areas. A total of 49 interventions have been identified for a total length of the pipeline modification of 9,805 m. Regarding the Accessibility Index (A), which shows in the first scenario a high level of vulnerability, portions of the pipeline farther from streets accessible from the mechanical vehicle have been identified and a total of 23 pipeline route modifications are also proposed to mitigate vulnerability due to accessibility issues, for a total length of the pipeline of 1,863 m (Table 8).

Table 8 | Second scenario: Proposed interventions to pipeline route for landslide effects mitigation and accessibility improvements

Type of intervention	Vulnerable elements	Number of interventions	Length of pipeline affected by modifications (m)
Land reinforcement for landslide mitigation	River crossing	6	355
	Street crossing	11	1,377
	Tunnel	4	2,852
	Railway crossing	3	446
Bypass in pipeline route	Pipeline route exposed to landslide	49	9,805
Pipeline route modification	Pipeline far from streets accessible from mechanical vehicle	23	1,863

The mitigation measures described above affect the vulnerability indicators. In particular, the proposed measures aim to improve mainly three aspects of the infrastructure vulnerabilities: (1) the diversification degree of water supply with the introduction of new water sources for the Messina City's water distribution network, which affects the Uniqueness Index (U); (2) the city-wide tank capacities and consequently the time period in which the city is not affected by pipeline breakage or malfunctions causing interruption in water supply, which affect the Index of Service Failure (F); and (3) the pipeline route itself, with proper modifications, which would lead to a decrease in vulnerability associated with landslides and accessibility issues, related to the Exposure Index of the Pipe (I_{EP}) and of Special Structures (I_{SS}) and the Accessibility Index (A).

All eight vulnerability indices are again evaluated for this second scenario introducing mitigation measures. Vulnerability indicator values are reported in Table 9, and in Figure 5, the vulnerability chart is represented with the Kiviat chart, to combine multi-indicator information.

In Figure 5, highlighted in light red are the differences in vulnerability indicator values evaluated after the introduction of mitigation measures above described, with respect to the first scenario configuration. It is possible to observe improvements in multiple indicators.

The Exposure Index of the Pipe to Landslides Index (I_{EP}) assumes in this scenario the value of 0.43, corresponding to a medium vulnerability (Table 9), with respect to its value in the first scenario, which is 0.73 corresponding to a high vulnerability (Table 7). The Exposure Index of the Special Structures to Landslides Index (I_{SS}) assumes in this second scenario the value of 0.36, corresponding to a medium vulnerability (Table 9), with respect to its value in the first scenario, which is 0.61 corresponding to a high vulnerability (Table 7). The Accessibility Index (A) assumes in this second scenario the value of 0.55, corresponding to a medium vulnerability (Table 9), with respect to its value in the first scenario, which is 0.89 corresponding to a high vulnerability (Table 7).

From the above-mentioned improvements in vulnerability indicators, it is apparent that land reinforcements and pipeline route modifications represent valid mitigation measures in vulnerability for landslides and accessibility issues.

The Uniqueness Index (U) assumes in this second scenario the value of 0.59, corresponding to a medium vulnerability (Table 9), with respect to its value in the first scenario, which is 0.83 corresponding to a high vulnerability (Table 7). This

Table 9 | Second scenario: Vulnerability indicator values for Fiumefreddo aqueduct after mitigation interventions

Indicator	Value	Vulnerability
M	0.3	Low/Medium
A_{ge}	0.58	Medium
I_{CA}	0.35	Medium
I_{EP}	0.43	Medium
F	0.89	High
U	0.59	Medium
A	0.55	Medium
I_{SS}	0.36	Medium

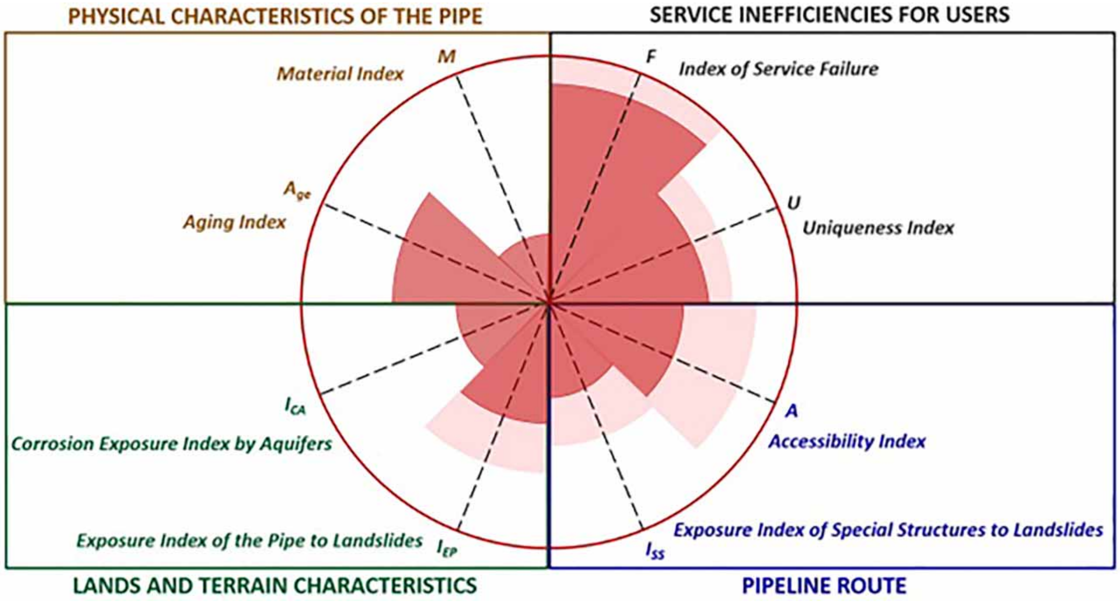


Figure 5 | Second scenario: Vulnerability chart for Fiumefreddo aqueduct after mitigation measures. The eight indicators are reported in red and named in the vulnerability chart, classified by categories. Highlighted in light red are reported differences between vulnerability indicators for Fiumefreddo aqueduct in its actual configuration (see 'First scenario simulation' in Figure 4) and in the second scenario configuration.

means that diversification in water supply is necessary to reduce vulnerability due to aqueduct infrastructure breakages and failures.

The Index of Service Failure (F) assumes in this second scenario the value of 0.89, still corresponding to a high vulnerability (Table 9), as in the first scenario with a value of 1 (Table 7). In this case, even if there is an improvement in the vulnerability indicator value, it is still a high vulnerability value, meaning that only the introduction of a new main tank in Messina City's water distribution network is not sufficient for substantially mitigating its vulnerability in the case of the Fiumefreddo aqueduct breakages. It follows that improving all tank capacities can be an effective way to mitigate vulnerabilities in this specific case.

No mitigation measures have been proposed in this scenario regarding protection from corrosion of the pipe by aquifers because the value of the Corrosion Exposure Index by Aquifers (I_{CA}) already had a medium level of vulnerability in the first scenario and has not been considered of primary interest in the second scenario. The Aging Index (A_{ge}) and the Material Index (M) also show no improvements in their values (Table 9) with respect to the first scenario (Table 7) because no interventions have been proposed that affect their values of medium vulnerability in both cases.

Results comparing the first and the second scenarios show how vulnerability indicators are sensitive to pre- and post-mitigation measures, giving positive feedback on the reliability of the methodology. In terms of improving evaluation and performance of the methodology, quantifiable in terms of the percentage of vulnerability reduction for each index, the Index of Service Failure (F) shows a reduction in vulnerability of 11%; the Uniqueness Index (U) shows a reduction in vulnerability of 28.9%; the Accessibility Index (A) shows a reduction in vulnerability of 38.2%; the Exposure Index of the Special Structures to Landslides Index (I_{SS}) and the Exposure Index of the Pipe to Landslides Index (I_{EP}) show the highest degree of reduction in vulnerability, of 40.9 and 41.1%, respectively. From this simple performance analysis, it is possible to understand which mitigation measures would be more effective for reducing the aqueduct vulnerabilities, which in this case were pipeline route modifications and land reinforcements, as they directly affect the indices which show better performances of A, I_{SS}, and $I_{EP.}$

CONCLUSIONS

This study proposes a methodology for vulnerability assessment of water supply infrastructure based on new vulnerability indicators. The need for such a method arises from real issues faced in the October 2015 breakage event of the Fiumefreddo aqueduct supplying the City of Messina (Italy), which served also as a case study to test the robustness of the methodology, here applied for the first time.

This methodology can be applied both to existing aqueducts and to new aqueducts in the planning phase. In fact, indicators have been created purposively to be adaptable to all areas and case studies, as they are dependent on parameters which are specific to every aqueduct and location. In the case of existing aqueducts, the application of this vulnerability analysis provides water managers a simple way to highlight specific vulnerabilities of their infrastructure and supports them in the decision-making process, for choosing proper mitigation measures and for planning specific interventions. In the case of new aqueducts in the planning phase, designers can apply this methodology to test the vulnerabilities of their design solutions.

From the application of the proposed methodology, it appears that indicators are easy to manage, and results produced by aggregating them into vulnerability charts represent a rapid approach to compare different scenario solutions and highlight improvement in mitigation measures. Also, from the comparison of the two scenario applications presented here, it appears that indicators are sensitive to pre- and post-mitigation measures, and this gives confirmation of the robustness and reliability of the methodology.

Future development of this work can be done by applying it to a new aqueduct in the planning phase and supporting designers in the pipeline route selection, to test the proposed vulnerability assessment methodology in different design solution comparisons.

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The authors declare there is no conflict.

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