



Received: 01 January 2018  
Accepted: 20 March 2018  
First Published: 26 March 2018

\*Corresponding author: D. Pantusa,  
Innovation Engineering Department,  
University of Salento, Lecce(LE) I-73100,  
Italy  
E-mail: [daniela.pantusa@unisalento.it](mailto:daniela.pantusa@unisalento.it)

Reviewing editor:  
Hamidi Abdul Aziz Universiti Sains  
Malaysia - Kampus Kejuruteraan Seri  
Ampangan, Malaysia

Additional information is available at  
the end of the article

## CIVIL & ENVIRONMENTAL ENGINEERING | RESEARCH ARTICLE

# Infrastructure Vulnerability Index of drinking water systems to terrorist attacks

M. Maiolo<sup>1</sup> and D. Pantusa<sup>2\*</sup>

**Abstract:** Drinking water supply systems are vulnerable targets for which counter-terrorism measures have been raised worldwide. The threat of terrorist attacks to these systems has led to the need for the international scientific community to deal with the vulnerability assessment related to such events. In this context, this paper proposes an Infrastructure Vulnerability Index for drinking water distribution system with the aim of providing managers with a tool to assess system vulnerability to possible terrorist acts and to support the investments choice aimed at increasing security. This index is obtained using a set of indicators with reference to the structural parts of the system and considers both intentional contamination and physical damage. The index uses a hierarchic structure and decomposes the system into components and uses the Analytic Hierarchy Process to compute the weights. An application of the index was carried out for three water schemes of the Province of Crotona (Southern Italy) and the results obtained allowed to highlight the characteristics of the index and its usefulness.

### ABOUT THE AUTHORS

M. Maiolo is associate professor at the Department of Environmental and Chemical Engineering, University of Calabria. His research interests are related to sustainable management of water resources, optimization of water resource management, hydraulic and maritime engineering, with specific experience in drinking water risk, drinking water consumption, drinking water supply systems. He is coordinator of Italian Regional Project (POR CALABRIA FESR 2014–2020)—Innovation and Competitiveness (I&C)—project: origAMI—original Advanced Metering Infrastructure.

D. Pantusa received the degree in Civil Engineering in 2002 from University of Calabria and her PhD degree from University of Calabria in 2007. She is currently Research Associate at the Department of Innovation Engineering, University of Salento. Her research activity is mainly focused on sustainable management of water resources, drinking water risk, drinking water supply systems, optimization of water resource management, drinking water consumption, hydraulic and maritime engineering.

### PUBLIC INTEREST STATEMENT

This paper deals with the vulnerability of drinking water supply systems against possible terrorist attacks. Drinking water supply systems are, in fact, vulnerable targets for which counter-terrorism measures have been raised worldwide. This paper proposes an Infrastructure Vulnerability Index obtained using a set of indicators with reference to the various structural parts of the system. This index allows for the assessment of the vulnerability of water supply systems as a function of the presence and/or absence of elements designed to reduce the possibility of terrorist attacks and to detect the occurred terrorist act in a timely manner. This index can be used by the managers to compare different water schemes in relation to their degree of vulnerability, to identify the infrastructural elements that most affect the level of vulnerability of a single system, to support the investments choice and to assess the effects of the interventions aimed at increasing security.

**Subjects: Reliability & Risk Analysis; Engineering Management; Civil, Environmental and Geotechnical Engineering; Water Engineering; Water Science; Hydraulic Engineering**

**Keywords: drinking water systems; infrastructure vulnerability index; intentional water contamination; physical damage; terrorist attacks; vulnerability assessment**

## 1. Introduction

The first years of this new century were marked by several terrorist attacks such as those in New York, Madrid, London, Ankara, Paris, the Ivory Coast, Brussels, Nice, Berlin and Istanbul. These attacks have brought the issue of security back to the international spotlight especially in relation to the difficulty of preventing such acts.

Some terrorist threats regard possible attacks on water distribution systems; water resources, in fact, have always been used as a target and an instrument of war and terrorism (Gleick, 1993, 2006).

The problem, of course, has assumed considerable dimensions, with frequent revelations of risks and terrorist attacks on water distribution systems. Recently in an interview with *The Sunday Times* the British Home Secretary said that aqueducts, transportation, crowded places and high interchange communities, are among the possible targets of terrorist attacks (Il Giornale, 2017). In a “confidential” report of the Turkish secret services it was argued that Isis was planning to poison water sources in Turkey with the aim of spreading different bacteria including those that cause tularemia, the so-called “rabbit fever” (Tgcom24, 2016). In 2012, 140 Afghan students and their teachers were admitted to a local hospital after drinking contaminated water from the their school’s water tank (CNN, 2012). In the Kashmir region in India, Maoist cadres allegedly poisoned a pond near a field of Central Reserve Police Force (The Times of India, 2010). While a man in Varney, West Virginia, was accused of having plans to poison the local water system with cyanide, but police were able to reach him first (WSAZ News, 2008). In Greve, Denmark, Inspectors discovered strychnine in the water supply of a Danish town during a routine check (UPI, 2006). In Britain, a staff member of Thames Water discovered that a water tank in Dancers End, just outside Tring, had been sabotaged (HSPDsHemeltoday News, 2006). A spokesman for al Qaeda has told an Arabic-language newsmagazine that the terror group will try to use poisons to attack the United States, specifically threatening to contaminate the nation’s water supply (The Washington Times, 2003). Italian police say they have arrested four Moroccans who were planning a chemical attack in Rome, targeting buildings which included the United States embassy (BBC News, 2002).

The abovementioned events highlight the need for the scientific community to take an interest in the aspects of vulnerability and risk related to drinking water supply systems regarding intentional contamination and physical damage.

Recently vulnerability assessment has gained a dynamic and complex nature, and has become an active area of research in view of its growing strategic importance in various fields of application (Ilker, Ahmet, & Ahmet, 2010). Vulnerability tends to mean different things in different contexts and it is often described using various terms such as “weakness”, “lack of capacity”, “exposure to hazard”. In literature, in fact, there are different definitions of vulnerability. According to Ezell (2007) vulnerability is defined as a measure of susceptibility to a scenario, and is therefore a condition of the system and should be evaluated in the context of a scenario. National Security Telecommunications Advisory Committee, NSTAC (1997) states that vulnerability is a function of access and exposure, while in the National Infrastructure Protection Plan (Department of Homeland Security & NIPP, 2013) vulnerability is defines as physical feature or operational attribute that renders an entity open to exploitation or susceptible to a given hazard.

Regarding water systems they are vulnerable to both manmade and natural threats including, e.g. earthquakes, flood, droughts, terrorist attacks. Safe drinking water is central to the life of an individual and of society; a drinking water contamination incident or the denial of drinking water

services would have far-reaching public health, economic, environmental, and psychological impacts. Other critical services such as fire protection, healthcare, and heating and cooling processes would also be disrupted by the interruption or cessation of drinking water service, resulting in significant consequences to the national or regional economies (Department of Homeland Security & US EPA, 2015). Therefore, the issue of the security and risk assessment of such systems is of increasing importance. In this context, numerous definitions exist for the variables of interest in a risk assessment study. These variables include: event or threat, outcome, scenario, exposure, vulnerability, consequences, risk.

Regarding vulnerability, Ezell (2007) argues that a relationship emerges from the literature between vulnerability and risk. Vulnerability highlights the notion of susceptibility to a scenario whereas risk focuses on the severity of consequences to a scenario. As described in Thomas (2006), the National Water Resource Association, NWRA (2002) defines a vulnerability assessment as the identification of weaknesses in security, focusing on defined threats that could compromise the ability to provide a service, while National Oceanic and Atmospheric Administration (2002), defines vulnerability as the susceptibility of resources/assets to negative impacts from threat events. Hence, a vulnerability assessment accounts for the assets that could deter or defray unwanted outcomes from an event and for their susceptibility to failure. Vulnerability is defined by Haimes and Horowitz (2004) to be the manifestation of the inherent states of a system (e.g. physical, technical, organizational, and cultural) that can be exploited by an adversary to cause harm or damage. Copeland (2010) identifies the most likely “vulnerable” water systems to be the relatively small number of water systems serving the largest populated cities in the country.

The terrorist events of recent years have increased the attention on the safety aspects of water infrastructure. In the United States, just after September 11, 2001, the United States Congress approved a series of acts pertaining to vulnerability assessments to assess potential threats to such systems and to identify corrective actions. Over the years various vulnerability assessment methodologies and tools were developed and several studies were conducted on this issue by various institutions not only in USA but worldwide (APWA, AMWA, NACWA, & WEF, 2007; Centre for European Reform [CER], 2005; HSPDs, 2002; Istituto Superiore di Sanità, 2005; US EPA, 2003, 2007, 2009, 2010).

Water systems are vulnerable to a range of intentional threats including contamination, damaged or sabotaged through physical destruction and cyber attack.

Consequences of a water contamination can be significant. A contamination event in a water system can adversely affect the people, the businesses, and the community it serves due to fear, loss of water service, significant economic costs for decontamination and recovery, and the magnitude of adverse public health effects (Clark & Hakim, 2014).

Physical damage has consequences mainly related to the interruption of service and may also cause large economic harms. Vulnerable characteristics of water systems include their physical attributes, e.g. reservoirs, tanks, and pump stations. In addition to physical attributes, a water utility’s SCADA could be vulnerable to cyber attack, for example, turning pumps on or off, filling or emptying tanks inappropriately, or causing water hammer events (Clark & Hakim, 2014).

In the last decades, the vulnerability of the water systems to possible terrorist attack was studied by several authors with reference to intentional physical damage, cyber attack and specially to intentional contamination aspects in relation to, e.g. types of contaminants, magnitude of potential consequences, influence of contaminant decay (Davis & Janke, 2011; Davis, Janke, & Magnuson, 2014; Di Nardo, Di Natale, Guida, & Musmarra, 2013; Di Nardo et al., 2015; Hickman, 1999; Murray, Janke, & Jim, 2004; Nilsson, Buchberqer, & Clark, 2005; Panguluri, Phillips, & Cusimano, 2011), and to the definition of an integral valuation framework of water system vulnerability (Ezell, 2007; Haimes, Matalas, Lambert, & Jackson, 1998; Tidwell, Cooper, & Silva, 2005).

In this context, the objective of the work described in this paper is the definition of an index of vulnerability of the drinking water supply systems with respect to possible terrorist acts, which can be used by the managers to compare different water schemes in relation to their degree of vulnerability, to identify the infrastructural elements that most affect the level of vulnerability of a single system, to support the investment choice and to assess the effects of the interventions aimed at increasing security.

In the definition of this index, the vulnerability refers to the system susceptibility to possible terrorist attacks in relation to the presence and/or absence of elements that can make the system more or less exposed to this threat. This index is a deterministic comparative type and is easily and immediately usable in management.

## 2. Materials and methods

Given the growing water demand, the sources pollution and the reduction of water availability due to climate change, all the aspects related to the correct system design, reliability assessment, operational efficiency, proper allocation of available water resources, remain scientific and engineering topics still of current interest (Carini, Maiolo, Pantusa, Chiaravalloti & Capano, 2017; Cunha & Sousa, 1999; Giustolisi, Laucelli, & Colombo, 2009; Maiolo & Pantusa, 2015, 2016, 2017a, 2017b; Maiolo, Mendicino, Pantusa, & Senatore, 2017; Samani & Mottaghi, 2006; Sun & Zeng, 2012). In recent years, however, growing is also the interest in the theme of threats to drinking water systems due to natural disasters and human-caused incidents. In particular, increasing concerns about the possibility of terrorist attacks towards drinking water systems have contributed to the need for new approaches to the vulnerability and security of these systems.

A terrorist attack on a water supply system can create greater damage the longer the delay with which it is discovered. In this type of terrorist attack, blatant actions are not accomplished, instead, the action is executed in secret, seeking to make surprise effect.

To guard against these types of attacks, it is possible to act trying to physically prevent access to water supply systems, and when the attack occurs, quickly detect the incident.

Needs and opportunities to reduce the vulnerability of public water systems to willful attack were reviewed by Haimes et al. (1998). The terrorist threat were described, classifying potential physical, chemical-biological, and cyber attacks to water systems. A hierarchical holographic model was introduced for multiple perspectives on the hardening of water systems. Types of hardening were defined, including security, robustness, resilience, and redundancy.

An approach of threat assessment of water supply systems using Markov Latent Effect (MLE) modeling was proposed by Tidwell et al. (2005). This method provides for the decomposition of a complex threat system into sub-systems or decision elements to track down a particular threat from its origin to the point of consequence. All decision elements are then aggregated and an assessment score was obtained which provided a measure of the credibility of a threat. The approach was applied to a real municipal water distribution system under two different attack: bomb and injection of a toxin; for each attack the level of system security has been evaluated.

Ezell (2007) proposed an Infrastructure Vulnerability Assessment Model (I-VAM) based on MAUT (Multi Attribute Utility Theory) and applied it to a medium-sized clean water system. In this model, the system is presented in a hierarchical structure and clean water system model decomposition serves as the structure of the value model with deterrence, detection, delay, and response value functions used to measure protection for system components.

US EPA (2015) developed the VSAT software tool to support water and wastewater utility in vulnerability assessments. VSAT is available, free of charge, for wastewater utilities, drinking water utilities, and for utilities providing both services. This tool was developed to help utilities in vulnerability assessment through identification of critical assets, threat, countermeasure, costs (Table 1).

**Table 1. Literature synthesis of vulnerability assessment of water systems to terrorist attacks**

Reference	Purpose	Method	Outcome
Haimes et al. (1998)	Analysis of the potential threats against water supply systems (physical, chemical/biological, and cyber threats)	The proposed hardening methodology was based on Hierarchical Holographic Modeling (HHM)	Types of hardening are defined. The paper provides a foundation for improving the assessment of the risk of willful attacks in the management of civil infrastructure systems
Tidwell et al. (2005)	Threat assessment of water supply systems	Threat assessment is based on Markov Latent Effect (MLE)	The paper proposes an alternative approach to rank the credibility of alternative threat scenarios
Ezell (2007)	Quantification of vulnerability through the Infrastructure Vulnerability Assessment Model (I-VAM)	The Infrastructure Vulnerability Assessment Model (I-VAM) is based on MAUT (Multi Attribute Utility Theory)	This paper asserts that vulnerability is a condition of the system and it can be quantified using the Infrastructure Vulnerability Assessment Model (I-VAM). The model is applied to a medium-sized clean water system
US EPA (2015)	Support water and wastewater utility in vulnerability assessments	Qualitative risk assessment methodology	Software tool which allows utilities to assess their vulnerabilities to both man-made and natural hazards and evaluate potential improvements to enhance their security and resilience

The work described in this paper fits into this context and proposes an infrastructure vulnerability index.

In comparison to the state of the art, the proposed index refers only to intentional attacks and does not refer, as in the case of the Haimes study and the US EPA tool, to attacks due to both man-made and natural hazards. Moreover, this index also refers not only to intentional contamination, which is the aspect most considered in the various studies conducted on this topic, but it also refers to intentional physical damage and cyber attack. The proposed index, in fact, allows for the quantitative assessment of the vulnerability of water supply systems as a function of the presence and/or absence of elements designed to reduce the possibility of the deliberate release of contaminants (bacteriological, chemical or nuclear) or the intentional physical damage, and to detect the occurred terrorist act in a timely manner. The index considers intentional contamination and physical damage/cyber attack separately and then makes an overall vulnerability assessment.

As the model proposed by Ezell, the index refers to the infrastructural vulnerability of the system, uses a hierarchic structure and decomposes the system into components. However, this index classifies the indicators in deterrence indicators and delay indicators and uses the Analytic Hierarchy Process (AHP) to compute the weights.

Finally, it should be noted that since the main addressees of this index are the water system managers, unlike other more complex models, this index was implemented so that it is an easy tool to use and require a low computational cost.

### 2.1. Infrastructural Vulnerability Index

The Infrastructural Vulnerability Index of the water system,  $IVI$ , is assessed through two sub-indices of vulnerability, one referring to intentional contamination,  $IVI_{IC}$ , and the other to the physical damage of the system and cyber attack,  $IVI_{PD}$ . The Infrastructural Vulnerability Index is calculated as follows:

$$IVI = w_{IC} \cdot IVI_{IC} + w_{ID} \cdot IVI_{PD} \tag{1}$$

where  $w_{IC}$  is the weight assigned to the  $IVI_{IC}$  sub-index and  $w_{PD}$  is the weight assigned to the  $IVI_{PD}$  sub-index.

The vulnerability is assessed through an index using a scores and weights methodology. The structure of each sub-index consists of pillars (Subsystem) that consider the different sub-systems components of the water scheme; each pillar is divided into a number of components, and each component is formed by a set of elementary indicators. The sub-index is obtained through a process that includes a first step of attribution of appropriate weights to the indicators, to the components and to the subsystems, and a subsequent phase of aggregation to switch to an index consisting of different levels. The indicators considered are passive and active; the passive indicators refer to elements determining a delay in the realization of the terrorist act, while the active type indicators refer to elements of deterrence and that allow the early detection of the terrorist act.

Regarding the structures of the two sub-indices, it is similar; there are small differences in the definition of some indicators and the sub-index referred to the physical damage,  $IVI_{PD}$ , includes the subsystem referred to SCADA and related components.

The total number of subsystems, components and indicators for the two sub-indices is described below (Table 2).

In literature, there are several techniques for the aggregation of the indicators and the choice of method which is best suited to characterize the phenomenon under examination depends on the data, in addition to the discretion and the analyst’s judgement. The most appropriate technique for the specific case under examination appears to be the one based on the distance from the target. The indicators taken as a reference for the vulnerability index are Boolean type, so the targets are related to the presence of devices capable of delaying or detecting the terrorist act, and it will assign the value of the unit. However, regarding the scores given to each indicator, they will have a value of 0 in the absence of active and passive elements, and a value of 1 in their presence.

The procedure for the sub-index construction includes a first aggregation at the indicator level, for each individual component, then a second aggregation at component level, and a third aggregation at subsystem level.

Considering for example the sub-index  $IVI_{IC}$ , for each  $j$  the value of the distance from the target,  $D_j$ , indicator is calculated such as:

$$D_j = I_{jc} / T_{jc}, \tag{2}$$

in which  $I_{jc}$  represents the Boolean value assigned to each indicator of the single component  $c$  (for  $c = 1, 2, \dots, C$ ).

The next step is the assignment of weights for each indicator of the  $c$ -th component. The aggregation is done through a weighted mean:

$$S_c = \sum (w_{1j} \times D_j) / \sum w_{1j}, \tag{3}$$

where  $w_{1j}$  is the weight of the indicator  $j$  of the component  $c$ .

**Table 2. Sub-indices structure—Number of subsystems, components and indicators for  $IVI_{IC}$  and  $IVI_{PD}$**

	$IVI_{IC}$	$IVI_{PD}$
Subsystems	5	6
Components	12	14
Indicators	14	49

At this point it is necessary to make a further aggregation in order to pass from single components, to subsystem. To each component will be assigned a weight,  $w_{2c}$ .

$$S_s = \sum (w_{2c} \times S_c) / \sum w_{2c}, \quad (4)$$

Lastly, it is necessary to make a further aggregation to switch from single subsystem to the Sub-index. To each subsystem will be assigned a weight,  $w_{3s}$ .

$$IVI_{IC} = \sum (w_{3s} \times S_s) / \sum w_{3s} \quad (5)$$

The same procedure is used to the  $IVI_{pd}$  sub-index.

The information obtained from the acts made available by the Managers in the activities to develop the report on drinking water systems (Istituto Superiore di Sanità, 2005), and the information obtained from the activities public and those to which an adequate classification of secrecy is attributed for the development of the relevant Italian legislation (Legislative Decree 61, 2011; Decree of the President of the Council of Ministers, 24 January 2013) allowed to get a first framework to quantify the vulnerability of drinking water systems. Such information has also allowed to evaluate the weight of the indicators as a function of the ability to delay the terrorist act, the accessibility of the site and the ability to transport adequate material to the terrorist act, the susceptibility to being subject to terrorist acts, the unauthorized access attempts, the historical occurrence of similar attacks, on the basis of the bibliography and public available information and classified as confidential.

The criteria for weighting were therefore defined on the basis of the technical experience and the information produced by the Managers.

In general, as for the allocation of weights, they were assigned considering the time of access to the infrastructure and the easiness to carry out the terrorist act. For the subsystem and the components greater importance has therefore been given to those infrastructural elements that are more likely to be chosen as targets of terrorist attacks for the easier accessibility and possibility of execution of the act, also in relation to acts which occurred historically; for individual indicators lower importance has been given to that represent passive elements and may cause a delay in the execution of the terrorist act and greater importance for indicators that represent active elements.

As regards intentional contamination, tanks, reservoirs, or pump stations are vulnerable to both contaminant release and contaminant injection. Pressurized backflow could theoretically occur anywhere in the distribution system and simply requires a pump with the necessary power to overcome the distribution system line pressure where the injection is to occur (Clark & Hakim, 2014). Problematic is the protection of river and lake which by territorial extension and number of access points does not allow the implementation of systems and procedures that create on the one hand a greater deterrence towards harmful actions and on the other a desirable growth of continuous and periodic checks. The volumes at stake, however, determine a natural dilution effect that increases the margins of intervention and protection of the quality of the water then distributed. For works under pressure, greater safety derives instead from the difficult attachment of these networks (Istituto Superiore di Sanità, 2005). In particular, for weight attribution, a greater weight has been attributed to storage and distribution system that are considered the most vulnerable elements of a water system. In fact, as reported in Clark and Hakim (2014) many studies cite post treatment storage facilities and the distribution system as being the most vulnerable components. Descending weight has been given to treatment, intake structure and conveyance, respectively.

As regards the sub-index  $IVI_{ID}$  elements that make the system particularly vulnerable are, e.g. pumping stations and valves. In fact, loss of water or a substantial loss of pressure could disable

fire-fighting capability, interrupt service, and disrupt public confidence. Many of the major pumps and power sources in water systems have custom-designed equipment and in case of a physical attack it could take months or longer to replace them. Sabotaging pumps that maintain flow and pressure could cause long-term disruption. Breaks can be induced by a system-wide hammer effect, which could be caused by opening or closing major control valves too rapidly (Clark & Hakim, 2014). Therefore, greater weight has been assigned to conveyance and distribution for the presence of valves and pumping stations, while a lower weight has been given to storage, treatment and intake structure. Damage to the control system is considered less important.

In order to compute the weights, the Analytic Hierarchy Process (AHP), proposed by Saaty (1980) was used.

The Analytic Hierarchy Process (AHP) is a useful tool for analyze complex decision-making and to set priorities and make the best decision, by reducing complex decisions to a series of pairwise comparisons, and then synthesizing the results. In addition, the AHP incorporates a useful technique for checking the consistency of the decision maker’s evaluations, thus reducing the bias in the decision-making process. The computations made by the AHP are always guided by the decision maker’s experience, and the AHP can thus be considered as a tool that is able to translate the evaluations, both qualitative and quantitative, made by the decision-maker into a multicriteria (Table 3).

In order to compute the weights for the different criteria, the AHP starts creating a pairwise comparison matrix  $A_{n \times n}$  where  $n$  is the number of criteria considered and  $a_{ij}$  is the numeric value resulting from the comparison between the criteria  $i$  and  $j$ . The value  $a_{ij} > 1$  when the criterion  $i$  is more important than the criterion  $j$ , while  $a_{ij} < 1$ , when the criterion  $i$  is less important than the criterion  $j$ . If two criteria have the same importance, then the value of  $a_{ij}$  is equal to 1. The following constraints applies:

$$a_{ij} \cdot a_{ji} = 1 \tag{6}$$

and

$$a_{ii} = 1 \quad \text{for all } i \tag{7}$$

**Table 3. The fundamental scale of AHP**

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally
2	Weak	
3	Moderate importance	Experience and judgment slightly
4	Moderate plus	
5	Strong importance	Experience and judgment strongly
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity $i$ has one of the above nonzero numbers assigned to it when compared with activity $j$ , then $j$ has the reciprocal value when compared with $i$	
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining $n$ numerical values to span the matrix



**Table 4. Average random consistency index (R.I.)**

<i>n</i>	1	2	3	4	5	6	7	8	9	10
Random consistency index (R.I.)	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

Paired comparison judgments in the AHP are applied to pairs of homogeneous elements. The fundamental scale of values to represent the intensities of judgments is shown in Table 4. This scale has been validated for effectiveness, not only in many applications by a number of people, but also through theoretical justification of what scale one must use in the comparison of homogeneous elements (Saaty & Vargas, 2012).

Obtained the pairwise comparison matrix *A*, to calculate the criteria weighing vector it is necessary to determine the maximum eigenvalue  $\lambda_{max}$  and its  $v_{\lambda}$  eigenvector. Normalizing the eigenvector  $v_{\lambda}$  so that the sum of its elements is equal to 1 it is possible to obtain the percentage weight.

The measure of inconsistency can be used to successively improve the consistency of judgments. The consistency index of a matrix of comparisons is given by  $C.I. = (\lambda_{max} - n)/(n - 1)$ . The consistency ratio (C.R.) is defines as:

$$C.R. = \frac{C.I.}{R.I.} \tag{8}$$

It is obtained by comparing the C.I. with the appropriate one of the following set (Table 4). If it is not less than 0.10, it is necessary to revise the judgments. The AHP includes a consistency index for an entire hierarchy. An inconsistency of 10 percent or less implies that the adjustment is small compared to the actual values of the eigenvector entries (Saaty & Vargas, 2012).

Below Tables 5 and 6 with the assignment of weights, according to AHP approach.

It should be noted that:

- with regard to alarm systems and video surveillance they refer to the perimeter alarm systems along fences and security doors at the entrance of the artifacts and video surveillance systems in the external and internal areas of the works;
- regarding S.C.A.D.A. systems they will need to take:
  - probes with a continuous measurement of all or some of the following parameters: turbidity, conductivity, pH, residual chlorine, redox potential, TOC (Total Organic Carbon), UV absorbance (Istituto Superiore di Sanità, 2005);
  - electromechanical valves, on which both routine and emergency actions can be performed, in order to prevent contaminated water from reaching the consumer;
- regarding S.C.A.D.A. systems in the distribution network they will adopt:
  - electromechanical valves to act on to perform both routine and emergency actions, in order to prevent contaminated water from reaching the user;
  - regarding the position and access of the intake structures and the distance from the shore, they are to be understood in relation to the difficulties of access and reachability;
  - regarding navigability, it is to be referred to lower accessibility, in case of a non-navigable lake;
  - with regard to the tanks of biological monitoring, in more important plants, it is to be referred to the presence of monitoring tanks that use fish of the salmonid family such as, for example, the rainbow trout (Istituto Superiore di Sanità, 2005);

**Table 5. IVI<sub>IC</sub> structure and weights**

Subsystem	Weight subsystem	Component	Weight component	Indicators	Weight indicators	
IVI <sub>IC</sub> _1 Intake structure	0.0761	IVI <sub>IC</sub> _1.1 Spring	0.1173	IVI <sub>IC</sub> _1.1.a Fence	0.044162	
				IVI <sub>IC</sub> _1.1.b Reinforced doors	0.121347	
				IVI <sub>IC</sub> _1.1.c Alarm and video surveillance systems	0.417246	
				IVI <sub>IC</sub> _1.1.d S.C.A.D.A with chemical and physical controls	0.417246	
		IVI <sub>IC</sub> _1.2 Well	0.0549		IVI <sub>IC</sub> _1.2.a Fence	0.044162
					IVI <sub>IC</sub> _1.2.b Reinforced doors	0.121347
					IVI <sub>IC</sub> _1.2.c Alarm and video surveillance systems	0.417246
					IVI <sub>IC</sub> _1.2.d S.C.A.D.A with chemical and physical controls	0.417246
		IVI <sub>IC</sub> _1.3 River- Stream	0.2619		IVI <sub>IC</sub> _1.3.a Position and access	0.06195
					IVI <sub>IC</sub> _1.3.b Fence	0.06195
					IVI <sub>IC</sub> _1.3.c Alarm and video surveillance systems	0.43805
					IVI <sub>IC</sub> _1.3.d S.C.A.D.A with chemical and physical controls	0.43805
		IVI <sub>IC</sub> _1.4 Lake	0.5659		IVI <sub>IC</sub> _1.4.a Navigability	0.0498
IVI <sub>IC</sub> _1.4.b Structure distance from shore	0.0498					
IVI <sub>IC</sub> _1.4.c Alarm and video surveillance systems	0.4502					
IVI <sub>IC</sub> _1.4.d S.C.A.D.A with chemical and physical controls	0.4502					
IVI <sub>IC</sub> _2 Conveyance	0.0385	IVI <sub>IC</sub> _2.1 Pipeline	0.1046	IVI <sub>IC</sub> _2.1.a Availability of working drawings	0.8333	
				IVI <sub>IC</sub> _2.1.b Material	0.1667	
		IVI <sub>IC</sub> _2.2 Valves	0.2578		IVI <sub>IC</sub> _2.2.a Well plate with closure	0.8333
					IVI <sub>IC</sub> _2.2.b Self-locking bolts	0.1667
					IVI <sub>IC</sub> _2.3 Pump Station	0.6376
					IVI <sub>IC</sub> _2.3.a Fence	0.0549
					IVI <sub>IC</sub> _2.3.b Reinforced doors	0.2619
IVI <sub>IC</sub> _2.3.c Alarm and video surveillance systems	0.5659					
IVI <sub>IC</sub> _2.3.d S.C.A.D.A	0.1173					
IVI <sub>IC</sub> _3 Treat	0.1603	IVI <sub>IC</sub> _3.1 Treatment plant	1	IVI <sub>IC</sub> _3.1.a Fence	0.0333	
				IVI <sub>IC</sub> _3.1.b Reinforced doors	0.1295	
				IVI <sub>IC</sub> _3.1.c Alarm and video surveillance systems	0.5164	
				IVI <sub>IC</sub> _3.1.d S.C.A.D.A with chemical and physical controls	0.0634	
				IVI <sub>IC</sub> _3.1.e Biological monitoring fish of salmonid	0.2574	
IVI <sub>IC</sub> _4 Store	0.3626	IVI <sub>IC</sub> _4.1 Tank	0.5	IVI <sub>IC</sub> _4.1.a Fence	0.0333	
				IVI <sub>IC</sub> _4.1.b Reinforced doors	0.1295	
				IVI <sub>IC</sub> _4.1.c Alarm and video surveillance systems	0.5164	
				IVI <sub>IC</sub> _4.1.d S.C.A.D.A with chemical and physical controls	0.2574	
				IVI <sub>IC</sub> _4.1.e Availability of rapid tests	0.0634	
		IVI <sub>IC</sub> _4.2 Divider	0.5		IVI <sub>IC</sub> _4.2.a Fence	0.0333
					IVI <sub>IC</sub> _4.2.b Reinforced doors	0.1295
					IVI <sub>IC</sub> _4.2.c Alarm and video surveillance systems	0.5164
					IVI <sub>IC</sub> _4.2.d S.C.A.D.A with chemical and physical controls	0.2574
					IVI <sub>IC</sub> _4.2.e Availability of rapid tests	0.0634
IVI <sub>IC</sub> _5 Distribu-tion	0.3626	IVI <sub>IC</sub> _5.1 Pipeline	0.1046	IVI <sub>IC</sub> _5.1.a Availability of working drawings	0.8333	

(Continued)

**Table 5. (Continued)**

Subsystem	Weight subsystem	Component	Weight component	Indicators	Weight indicators
				IVI <sub>IC</sub> -5.1.b Material	0.1667
		IVI <sub>IC</sub> -5.2 Valves	0.2578	IVI <sub>IC</sub> -5.2.a Well plate with closure	0.8333
				IVI <sub>IC</sub> -5.2.b Self-locking bolts	0.1667
		IVI <sub>IC</sub> -5.3 Pump Station	0.6376	IVI <sub>IC</sub> -5.3.a Fence	0.0424
				IVI <sub>IC</sub> -5.3.b Reinforced doors	0.2009
				IVI <sub>IC</sub> -5.3.c Well plate with closure	0.0860
				IVI <sub>IC</sub> -5.3.d Alarm and video surveillance systems	0.4698
				IVI <sub>IC</sub> -5.3.e S.C.A.D.A	0.2009

- as regards rapid tests, they refer to the possibility of performing *in situ* tests for the detection of numerous toxic agents that can be either biological or chemical agents (Istituto Superiore di Sanità, 2005).

It should be also noted that in a water system more components of the same type but with different characteristics corresponding to different values of the indicators may be present. A water system, in fact, can be constituted by a certain number *n* of springs, wells, tanks, etc. In this case, made the first aggregation at the elementary indicators level for each of the *n* components of the same type, the value to consider for the subsequent phase of aggregation is obtained by performing a weighted mean with respect to the value of a homogeneous element related to that type of component. In particular:

- weighted average compared to the flow rates of each intake structure
- weighted average compared to the percentage of length in the case of pipelines
- weighted average, compared to the percentage of the number of works with the same characteristics in the case of valves and wells
- weighted average compared to the percentage of raised flow/drinkable by each plant in the case of pump station and water treatment plant
- weighted average compared to the percentage of water volume in the case of tanks and dividers.

The value of IVI<sub>IC</sub> and IVI<sub>PD</sub> varies between 0 and 1. The value of IVI is calculated as described in equation 1.

As regards the relative importance of the two sub-indices it is to be noted that contaminant threats are generally identified as the primary threat to water systems. While disruption of water service due to some type of physical destruction is often identified, most studies rank such denial of service or disruption-based attacks below those of contamination, both in terms of magnitude of impact (cost and public health) and the length in time of the disruption (Clark & Hakim, 2014).

On the basis of such consideration, the values assigned to  $w_{IC}$  and  $w_{PD}$  are:

$$w_{IC} = 0.6; \quad w_{PD} = 0.4 \tag{9}$$

The value of IVI varies between 0 and 1. The values of IVI have then been clustered in the following 3 categories:

**Table 6. IVI<sub>pd</sub> structure and weights**

Subsystem	Weight subsystem	Component	Weight component	Indicators	Weight indicators
IVI <sub>pd-1</sub> Intake structure	0.1125	IVI <sub>pd-1.1</sub> Spring	0.1245	IVI <sub>pd-1.1.a</sub> Fence	0.044162
				IVI <sub>pd-1.1.b</sub> Reinforced doors	0.121347
				IVI <sub>pd-1.1.c</sub> Alarm and video surveillance systems	0.417246
				IVI <sub>pd-1.1.d</sub> S.C.A.D.A with chemical and physical controls	0.417246
		IVI <sub>pd-1.2</sub> Well	0.1245	IVI <sub>pd-1.2.a</sub> Fence	0.044162
				IVI <sub>pd-1.2.b</sub> Reinforced doors	0.121347
				IVI <sub>pd-1.2.c</sub> Alarm and video surveillance systems	0.417246
				IVI <sub>pd-1.2.d</sub> S.C.A.D.A with chemical and physical controls	0.417246
	IVI <sub>pd-1.3</sub> River-Stream	0.3755	IVI <sub>pd-1.3.a</sub> Position and access	0.06195	
			IVI <sub>pd-1.3.b</sub> Fence	0.06195	
			IVI <sub>pd-1.3.c</sub> Alarm and video surveillance systems	0.43805	
			IVI <sub>pd-1.3.d</sub> S.C.A.D.A with chemical and physical controls	0.43805	
	IVI <sub>pd-1.4</sub> Lake	0.3755	IVI <sub>pd-1.4.a</sub> Navigability	0.0498	
			IVI <sub>pd-1.4.b</sub> Structure distance from shore	0.0498	
			IVI <sub>pd-1.4.c</sub> Alarm and video surveillance systems	0.4502	
			IVI <sub>pd-1.4.d</sub> S.C.A.D.A with chemical and physical controls	0.4502	
IVI <sub>pd-2</sub> Conveyance	0.3082	IVI <sub>pd-2.1</sub> Pipeline	0.1420	IVI <sub>pd-2.1.a</sub> Availability of working drawings	0.8333
				IVI <sub>pd-2.1.b</sub> Material	0.1667
	IVI <sub>pd-2.2</sub> Valves	0.4290	IVI <sub>pd-2.2.a</sub> Well plate with closure	0.8333	
			IVI <sub>pd-2.2.b</sub> Self-locking bolts	0.1667	
	IVI <sub>pd-2.3</sub> Pump Station	0.4290	IVI <sub>pd-2.3.a</sub> Fence	0.0549	
			IVI <sub>pd-2.3.b</sub> Reinforced doors	0.2619	
			IVI <sub>pd-2.3.c</sub> Alarm and video surveillance systems	0.5659	
			IVI <sub>pd-2.3.d</sub> S.C.A.D.A	0.1173	
IVI <sub>pd-3</sub> Treat	0.1125	IVI <sub>pd-3.1</sub> Treatment plant	1	IVI <sub>pd-3.1.a</sub> Fence	0.0333
				IVI <sub>pd-3.1.b</sub> Reinforced doors	0.1295
				IVI <sub>pd-3.1.c</sub> Alarm and video surveillance systems	0.5164
				IVI <sub>pd-3.1.d</sub> S.C.A.D.A with chemical and physical controls	0.0634
IVI <sub>pd-4</sub> Store	0.1125	IVI <sub>pd-4.1</sub> Tank	0.5	IVI <sub>pd-4.1.a</sub> Fence	0.0333
				IVI <sub>pd-4.1.b</sub> Reinforced doors	0.1295
				IVI <sub>pd-4.1.c</sub> Alarm and video surveillance systems	0.5164
				IVI <sub>pd-4.1.d</sub> S.C.A.D.A with chemical and physical controls	0.2574
				IVI <sub>pd-4.1.e</sub> Availability of rapid tests	0.0634
	IVI <sub>pd-4.2</sub> Divider	0.5	IVI <sub>pd-4.2.a</sub> Fence	0.0333	
			IVI <sub>pd-4.2.b</sub> Reinforced doors	0.1295	
			IVI <sub>pd-4.2.c</sub> Alarm and video surveillance systems	0.5164	
			IVI <sub>pd-4.2.d</sub> S.C.A.D.A with chemical and physical controls	0.2574	
			IVI <sub>pd-4.2.e</sub> Availability of rapid tests	0.0634	

(Continued)

**Table 6. (Continued)**

Subsystem	Weight subsystem	Component	Weight component	Indicators	Weight indicators	
IVI <sub>PD-5</sub> Distribution	0.3082	IVI <sub>PD-5.1</sub> Pipeline	0.1420	IVI <sub>PD-5.1.a</sub> Availability of working drawings	0.8333	
				IVI <sub>PD-5.1.b</sub> Material	0.1667	
		IVI <sub>PD-5.2</sub> Valves	0.4290	IVI <sub>PD-5.2.a</sub> Well plate with closure	0.8333	
				IVI <sub>PD-5.2.b</sub> Self-locking bolts	0.1667	
		IVI <sub>PD-5.3</sub> Pump Station	0.4290		IVI <sub>PD-5.3.a</sub> Fence	0.0424
					IVI <sub>PD-5.3.b</sub> Reinforced doors	0.2009
					IVI <sub>PD-5.3.c</sub> Well plate with closure	0.0860
					IVI <sub>PD-5.3.d</sub> Alarm and video surveillance systems	0.4698
IVI <sub>PD-5.3.e</sub> S.C.A.D.A	0.2009					
IVI <sub>PD-6</sub> Control	0.0460	IVI <sub>PD-6.1</sub> S.C.A.D.A.	1	IVI <sub>PD-6.1.a</sub> Use of international safety standards	0.5	
				IVI <sub>PD-6.1.b</sub> Physical systems presidium	0.5	

- High vulnerability ( $0 < IVI \leq 0.33$ )
- Medium vulnerability ( $0.33 < IVI \leq 0.66$ )
- Low vulnerability ( $0.66 < IVI \leq 1$ )

### 3. Application of the infrastructure vulnerability index in the province of Crotona

With reference to the Infrastructure Vulnerability Index described above, a first application was made in the province of Crotona, region Calabria, Southern Italy. In particular three drinking water systems have been taken as a reference: one small, one medium and one large. The systems size refers to the complexity and territorial extension of the infrastructures. This application was carried out to validate the index and to demonstrate its usefulness in planning of management strategies to prevent and reduce the vulnerability of water systems against possible terrorist attacks.

The first water scheme is the “Neto” scheme that serves a total of approximately 68,000 inhabitants. This system consists of:

- An intake structure on the river Neto
- About 120 km of pipelines in hard materials such as prestressed concrete, steel, cast iron, and only 2 in HDPE (conveyance);
- 2 water treatment plant;
- 8 underground reinforced concrete dividers;
- 18 underground concrete tanks;
- 11 networks for a total length of about 184 km, of different materials (steel, cast iron and HDPE), 1 long network 10 km in asbestos-cement;
- There are no SCADA systems;

The second water scheme is the scheme named “Pulitrea-Sila Badiale” serving a total of about 9300 inhabitants. This scheme comprises:

- 4 sources
- about 60 km of steel conveyance
- 10 underground reinforced concrete dividers
- 12 underground concrete tanks

- 10 steel and cast iron networks.
- There are no SCADA systems.

The third water system is the scheme named “Lese-Lipuda” serving approximately 52,000 inhabitants. This scheme comprises:

- 1 source, 1 well, 1 river intake structure
- 1 treatment plant
- about 167 km of conveyance
- 43 dividers
- 27 underground concrete tanks
- 20 steel and cast iron networks.

There are no SCADA systems.

The following Tables 7, 8 and 9 synthetically show the obtained results for sub-index  $IVI_{IC}$  and sub-index  $IVI_{PD}$  for the three schemes.

By applying the above procedure to the three water schemes, the values of  $IVI_{IC}$  and  $IVI_{PD}$  obtained are the following (Table 10):

By applying Equation (1), the values of IVI obtained for the three schemes are (Table 11):

The results obtained reflect the condition of vulnerable water schemes as the systems are not provided with alarm systems nor with video surveillance, nor with SCADA systems, and are also vulnerable to the effect of absence of other elements such as reinforced doors and valves with self-locking bolts (Table 11).

The application of the index to the three drinking water supply systems was conducted with the following objectives:

- Test the index to assess its applicability, the degree of complexity of the phase of collection and organization of input data, the computational burden, and to bring out any critical issues;
- Demonstrate the ability of managers to use this index to compare different water schemes in relation to their degree of vulnerability in order to identify the schemes that require intervention priority;
- Demonstrate the usefulness of the index in the evaluation of the infrastructural elements of a single drinking water system that most affect the level of overall vulnerability in order to direct investments especially in conditions of budget constraints;
- Demonstrate the ability to easily use this index to generate user-driven scenario, for example, to make assessments of the effects of possible interventions on the level of vulnerability.

Regarding the first point, the application made to the three water schemes has demonstrated the feasibility of the index and no critical issues have emerged; the collection of input data is obviously linked to the degree of complexity of the water scheme analyzed but the data are easily available, especially in case of managers having an adequate information system, and the computational burden were not excessive.

In the case of the province of Crotona the three water systems are managed by a single manager; this allowed to demonstrate the usefulness of the proposed index with respect to the possibility for manager to compare and classify the systems by vulnerability level and to make assessments on

**Table 7. Results for “Neto” scheme**

Component	Indicators	$D_j$	Sub-index $IVI_{IC}$			Sub-index $IVI_{PD}$		
			Sc	Ss	$IVI_{IC}$	Sc	Ss	$IVI_{PD}$
IVI <sub>IC</sub> -1.3River	IVI <sub>IC</sub> -1.3.a	0	0	0	0.209	0	0	0.224
	IVI <sub>IC</sub> -1.3.b	0						
	IVI <sub>IC</sub> -1.3.c	0						
	IVI <sub>IC</sub> -1.3.d	0						
IVI <sub>IC</sub> -2.1 Pipeline 1	IVI <sub>IC</sub> -2.1.a	1	0.989	0.138		0.989	0.164	
	IVI <sub>IC</sub> -2.1.b	1						
IVI <sub>IC</sub> -2.1 Pipeline 2	IVI <sub>IC</sub> -2.1.a	0						
	IVI <sub>IC</sub> -2.1.b	0						
IVI <sub>IC</sub> -2.2 Valves	IVI <sub>IC</sub> -2.2.a	0	0			0		
	IVI <sub>IC</sub> -2.2.b	0						
IVI <sub>IC</sub> -2.3 Pump Station	IVI <sub>IC</sub> -2.3.a	1	0.055			0.055		
	IVI <sub>IC</sub> -2.3.b	0						
	IVI <sub>IC</sub> -2.3.c	0						
	IVI <sub>IC</sub> -2.3.d	0						
IVI <sub>IC</sub> -3.1 Treatment plant 1	IVI <sub>IC</sub> -3.1.a	1	0.544	0.544		0.733	0.733	
	IVI <sub>IC</sub> -3.1.b	0						
	IVI <sub>IC</sub> -3.1.c	1						
	IVI <sub>IC</sub> -3.1.d	0						
	IVI <sub>IC</sub> -3.1.e	0						
IVI <sub>IC</sub> -3.1 Treatment plant 2	IVI <sub>IC</sub> -3.1.a	1						
	IVI <sub>IC</sub> -3.1.b	0						
	IVI <sub>IC</sub> -3.1.c	0						
	IVI <sub>IC</sub> -3.1.d	0						
	IVI <sub>IC</sub> -3.1.e	0						
IVI <sub>IC</sub> -4.1 Tank	IVI <sub>IC</sub> -4.1.a	1	0.033	0.033		0.033	0.033	
	IVI <sub>IC</sub> -4.1.b	0						
	IVI <sub>IC</sub> -4.1.c	0						
	IVI <sub>IC</sub> -4.1.d	0						
	IVI <sub>IC</sub> -4.1.e	0						
IVI <sub>IC</sub> -4.2 Divider	IVI <sub>IC</sub> -4.2.a	1	0.033			0.033		
	IVI <sub>IC</sub> -4.2.b	0						
	IVI <sub>IC</sub> -4.2.c	0						
	IVI <sub>IC</sub> -4.2.d	0						
	IVI <sub>IC</sub> -4.2.e	0						
IVI <sub>IC</sub> -5.1 Pipeline	IVI <sub>IC</sub> -5.1.a	1	1	0.289		1	0.249	
	IVI <sub>IC</sub> -5.1.b	1						
IVI <sub>IC</sub> -5.2 Valves	IVI <sub>IC</sub> -5.2.a	0	0			0		
	IVI <sub>IC</sub> -5.2.b	0						

water schemes that need priority actions. The results obtained for the three systems analyzed show a particular situation as they have the same levels of vulnerability; in this case manager should program interventions on all three water systems or, depending on the financial availability, could make evaluations on the priority of interventions considering the hierarchy of values obtained (even if

**Table 8. Results for “Pulitrea—Sila Badiale” scheme**

Component	Indicators	$D_j$	Sub-index $IVI_{IC}$			Sub-index $IVI_{PD}$		
			Sc	Ss	$IVI_{IC}$	Sc	Ss	$IVI_{PD}$
IVI <sub>IC</sub> -1.1 Spring (1,2,3)	IVI <sub>IC</sub> -1.1.a	1	0.038	0.038	0.149	0.038	0.038	0.161
	IVI <sub>IC</sub> -1.1.b	0						
	IVI <sub>IC</sub> -1.1.c	0						
	IVI <sub>IC</sub> -1.1.d	0						
IVI <sub>IC</sub> -1.1 Spring (4)	IVI <sub>IC</sub> -1.2.a	0	0.038	0.038	0.149	0.038	0.038	0.161
	IVI <sub>IC</sub> -1.2.b	0						
	IVI <sub>IC</sub> -1.2.c	0						
	IVI <sub>IC</sub> -1.2.d	0						
IVI <sub>IC</sub> -2.1 Pipeline	IVI <sub>IC</sub> -2.1.a	1	1	0.139	0.149	1	0.165	0.161
	IVI <sub>IC</sub> -2.1.b	1						
IVI <sub>IC</sub> -2.2 Valves	IVI <sub>IC</sub> -2.2.a	0	0	0.139	0.149	0	0.165	0.161
	IVI <sub>IC</sub> -2.2.b	0						
IVI <sub>IC</sub> -2.3 Pump Station	IVI <sub>IC</sub> -2.3.a	1	0.055	0.139	0.149	0.055	0.165	0.161
	IVI <sub>IC</sub> -2.3.b	0						
	IVI <sub>IC</sub> -2.3.c	0						
	IVI <sub>IC</sub> -2.3.d	0						
	IVI <sub>IC</sub> -3.1.b	1						
	IVI <sub>IC</sub> -3.1.c	0						
	IVI <sub>IC</sub> -3.1.d	0						
	IVI <sub>IC</sub> -3.1.e	0						
IVI <sub>IC</sub> -4.1 Tank	IVI <sub>IC</sub> -4.1.a	0	0.033	0.033	0.149	0.033	0.033	0.161
	IVI <sub>IC</sub> -4.1.b	1						
	IVI <sub>IC</sub> -4.1.c	0						
	IVI <sub>IC</sub> -4.1.d	0						
	IVI <sub>IC</sub> -4.1.e	0						
IVI <sub>IC</sub> -4.2 Divider	IVI <sub>IC</sub> -4.2.a	0	0.033	0.033	0.149	0.033	0.033	0.161
	IVI <sub>IC</sub> -4.2.b	0						
	IVI <sub>IC</sub> -4.2.c	1						
	IVI <sub>IC</sub> -4.2.d	0						
	IVI <sub>IC</sub> -4.2.e	0						
IVI <sub>IC</sub> -5.1 Pipeline	IVI <sub>IC</sub> -5.1.a	1	1	0.289	0.149	1	0.249	0.161
	IVI <sub>IC</sub> -5.1.b	0						
IVI <sub>IC</sub> -5.2 Valves	IVI <sub>IC</sub> -5.2.a	1	0	0.289	0.149	0	0.249	0.161
	IVI <sub>IC</sub> -5.2.b	0						

referring to the same category of vulnerabilities) or other elements as, for example, the population size served by the systems.

Regarding the third point, from the analysis of the results described above, it is possible to highlight the elements which have greater impact on the vulnerability of each systems. For the three systems analyzed these elements are similar; regarding the intentional contamination, for each of the three systems, the element which has greater impact is principally the storage due for the absence of reinforced doors, alarm and video surveillance systems, SCADA, rapid tests. Other elements are the absence of well plate with closure and self-locking bolts for valves (conveyance and



**Table 9. Results for “Lese-Lipuda” scheme**

Component	Indicators	$D_j$	Sub-index $IVI_{IC}$			Sub-index $IVI_{PD}$		
			Sc	Ss	$IVI_{IC}$	Sc	Ss	$IVI_{PD}$
IVI <sub>IC</sub> -1.1 Spring	IVI <sub>IC</sub> -1.1.a	1	0.044	0.055	0.132	0.044	0.055	0.149
	IVI <sub>IC</sub> -1.1.b	0						
	IVI <sub>IC</sub> -1.1.c	0						
	IVI <sub>IC</sub> -1.1.d	0						
IVI <sub>IC</sub> -1.2 Well	IVI <sub>IC</sub> -1.2.a	1	0.044			0.044		
	IVI <sub>IC</sub> -1.2.b	0						
	IVI <sub>IC</sub> -1.2.c	0						
	IVI <sub>IC</sub> -1.2.d	0						
IVI <sub>IC</sub> -1.3 River	IVI <sub>IC</sub> -1.3.a	1	0.062			0.062		
	IVI <sub>IC</sub> -1.3.b	0						
	IVI <sub>IC</sub> -1.3.c	0						
	IVI <sub>IC</sub> -1.3.d	0						
IVI <sub>IC</sub> -2.1 Pipeline	IVI <sub>IC</sub> -2.1.a	1	1	0.139		1	0.165	
	IVI <sub>IC</sub> -2.1.b	1						
IVI <sub>IC</sub> -2.2 Valves	IVI <sub>IC</sub> -2.2.a	0	0			0		
	IVI <sub>IC</sub> -2.2.b	0						
IVI <sub>IC</sub> -2.3 Pump Station	IVI <sub>IC</sub> -2.3.a	1	0.055			0.055		
	IVI <sub>IC</sub> -2.3.b	0						
	IVI <sub>IC</sub> -2.3.c	0						
	IVI <sub>IC</sub> -2.3.d	0						
IVI <sub>IC</sub> -3.1 Treatment plant 1	IVI <sub>IC</sub> -3.1.a	1	0.033	0.033		0.045	0.0045	
	IVI <sub>IC</sub> -3.1.b	0						
	IVI <sub>IC</sub> -3.1.c	0						
	IVI <sub>IC</sub> -3.1.d	0						
	IVI <sub>IC</sub> -3.1.e	0						
IVI <sub>IC</sub> -4.1 Tank	IVI <sub>IC</sub> -4.1.a	1	0.033	0.033		0.033	0.033	
	IVI <sub>IC</sub> -4.1.b	0						
	IVI <sub>IC</sub> -4.1.c	0						
	IVI <sub>IC</sub> -4.1.d	0						
	IVI <sub>IC</sub> -4.1.e	0						
IVI <sub>IC</sub> -4.2 Divider	IVI <sub>IC</sub> -4.2.a	1	0.033			0.033		
	IVI <sub>IC</sub> -4.2.b	0						
	IVI <sub>IC</sub> -4.2.c	0						
	IVI <sub>IC</sub> -4.2.d	0						
	IVI <sub>IC</sub> -4.2.e	0						
IVI <sub>IC</sub> -5.1 Pipeline	IVI <sub>IC</sub> -5.1.a	0	1	0.289		1	0.249	
	IVI <sub>IC</sub> -5.1.b	1						
IVI <sub>IC</sub> -5.2 Valves	IVI <sub>IC</sub> -5.2.a	1	0			0		
	IVI <sub>IC</sub> -5.2.b	0						

distribution) and the absence of fence, alarm and video surveillance systems and Scada for pump station and finally the river intake and treat where present. Regarding  $IVI_{PD}$ , distribution and conveyance are the elements which most influence the vulnerability value. Other elements of minor impact on the vulnerability of the system are storage, river intake and treat.

**Table 10.  $IVI_{IC}$  and  $IVI_{PD}$  for the three schemes**

Drinking water system	$IVI_{IC}$	$IVI_{PD}$
“Neto”	0.209	0.224
“Pulitrea-Sila Badiale”	0.149	0.161
“Lese-Lipuda”	0.132	0.149

**Table 11. Infrastructure Vulnerability Index IVI for the three schemes**

Drinking water system	Infrastructure Vulnerability Index IVI	Vulnerability category
“Neto”	0.215	High vulnerability
“Pulitrea-Sila Badiale”	0.154	High vulnerability
“Lese-Lipuda”	0.139	High vulnerability

Finally, to demonstrate the ability to easily use this index to generate user-driven scenario, the variation of the Infrastructure Vulnerability Index was evaluated in relation to some possible corrective interventions for the “Neto” scheme. The considered interventions are:

- insertion at the river intake structure of an alarm system and video surveillance
- insertion at the pump station of a reinforced door, an alarm system and video surveillance
- insertion at the water treatment plants of a reinforced door, an alarm system and video surveillance
- insertion at tanks and dividers of reinforced doors.

By performing these actions, the sub-index  $IVI_{IC}$  assumes the value of  $IVI_{IC} = 0.332$ , the sub-index  $IVI_{PD}$  assumes the value of  $IVI_{PD} = 0.378$ . The Infrastructure Vulnerability Index assumes the value of  $IVI = 0.35$ , medium vulnerability. The cost needed for these interventions is approximately € 70,000. Considering the number of users served by this water scheme, it can be considered to be definitely convenient to carry out the interventions and increase the security level of the system.

#### 4. Conclusion

Safety in drinking water distribution systems is increasingly important in relation to the increase of threats of possible terrorist attacks. The approach requires tools for assessing the vulnerability of systems with respect to terrorist actions in order to plan interventions of prevention.

This paper proposes an index of vulnerability, IVI, which analyzes the vulnerability of drinking water supply systems with reference to infrastructural aspects and in relation to the presence of elements that delay/deter a terrorist act, or allow rapid detection of the act. The proposed index intends to provide a framework of critical components of drinking water systems. The index developed is a deterministic-comparative type and allows to analyze the vulnerability levels of different water supply systems.

The proposed index allows to assess the infrastructural vulnerability of water systems to possible terrorist acts, considering both the aspect of intentional contamination and the aspect of physical damage to the works. The index presents a fast calculation procedure with low computational cost and does not require a large amount of information.

The application carried out for three water schemes made it possible to test the index and to evaluate its practical use. The results obtained have shown that this index can be considered a useful tool for the managers because it allowed to compare, without excessive computational burdens and difficulties in the collection of input data, the degree of vulnerability of different water systems.

The application also made it possible to assess the structural elements of the individual systems that require priority actions to reduce the level of vulnerability. The application has also allowed to highlight how even the few and not prohibitively expensive structural interventions, in economic terms, can increase the security of existing systems. For the construction of new systems, however, it is important to take safety aspects into account in the design phase.

This index, therefore, can be used by the managers but also by all the stakeholders of the sectors, to make estimates and comparisons of the vulnerability of the various systems, to make rapid assessments of the effects, in terms of vulnerability, of possible interventions to be implemented on the systems, to guide technical and investment choices for enhancement of the infrastructure in order to lower vulnerability.

#### Funding

The research was supported by Italian Regional Project (POR CALABRIA FESR 2014–2020)—Innovation and Competitiveness (I&C)—project: origAMI – original Advanced Metering Infrastructure.

#### Author details

M. Maiolo<sup>1</sup>

E-mail: [mario.maiolo@unical.it](mailto:mario.maiolo@unical.it)

ORCID ID: <http://orcid.org/0000-0002-6208-1307>

D. Pantusa<sup>2</sup>

E-mail: [daniela.pantusa@unisalento.it](mailto:daniela.pantusa@unisalento.it)

ORCID ID: <http://orcid.org/0000-0003-3450-252X>

<sup>1</sup> Department of Environmental and Chemical Engineering, University of Calabria, Rende I-87036, Italy.

<sup>2</sup> Innovation Engineering Department, University of Salento, Lecce(LE) I-73100, Italy.

#### Citation information

Cite this article as: Infrastructure Vulnerability Index of drinking water systems to terrorist attacks, M. Maiolo & D. Pantusa, *Cogent Engineering* (2018), 5: 1456710.

#### References

- APWA, AMWA, NACWA, & WEF. (2007). Protecting the water sector from security threats: The emerging legal and policy frameworks. Retrieved from <https://www.amwa.net/galleries/default-file/SecurityPublicationFinal2.pdf>
- BBC News. (2002). Cyanide attack foiled in Italy. Retrieved from <http://news.bbc.co.uk/2/hi/europe/1831511.stm>
- Carini, M., Maiolo, M., Pantusa, D., Chiaravallotti, F., & Capano, G. (in press). Modelling and optimization of least-cost water distribution networks with multiple supply sources and users: A Matlab-based approach. *Ricerche di Matematica*. doi:10.1007/s11587-017-0343-y
- CER. (2005). The EU and counter-terrorism. London: Centre for European Reform. Retrieved October 30, 2017, from <http://library.coleurop.be/pdf/CER/keohane.pdf>
- Clark, R. M., & Hakim, S. (2014). *Securing water and wastewater systems*. Cham: Springer International. <https://doi.org/10.1007/978-3-319-01092-2>
- CNN. (2012). *Extremists poison schoolgirls' water, Afghan officials say*. Retrieved from <http://edition.cnn.com/2012/04/17/world/afghanistan-girls-poisoned/>
- Copeland, C. (2010) *Terrorism and security issues facing the water infrastructure sector*. Congressional Research Service, 7-5700. Retrieved from <https://fas.org/sgp/crs/terror/RL32189.pdf>
- Cunha, M. D. C., & Sousa, J. (1999). Water distribution network design optimization: Simulated annealing approach. *Journal of Water Resources Planning and Management*, 125(4), 215–221. doi:10.1061/(ASCE)0733-9496
- Davis, M. J., & Janke, R. (2011). Patterns in potential impacts associated with contamination events in water distribution systems. *Journal of Water Resources Planning and Management*, 137, 1–9. doi:10.1061/(ASCE)WR.1943-5452.0000084
- Davis, M. J., Janke, R., & Magnuson, M. (2014). A framework for estimating the adverse health effects of contamination events in water distribution systems and its application. *Risk Analysis*, 34, 498–513. doi:10.1111/risa.12107
- Department of Homeland Security, & NIPP. (2013). *Partnering for critical infrastructure security and resilience*. Retrieved from <https://www.dhs.gov/sites/default/files/publications/national-infrastructure-protection-plan-2013-508.pdf>
- Department of Homeland Security and US EPA. (2015). *Water and wastewater system sector-specific plan, 2015*. Retrieved from <https://www.dhs.gov/sites/default/files/publications/nipp-ssp-water-2015-508.pdf>
- Di Nardo, A., Di Natale, M., Guida, M., & Musmarra, D. (2013). Water network protection from intentional contamination by sectorization. *Water Resources Management*, 27, 1837–1850. doi:10.1007/s11269-012-0133-y
- Di Nardo, A., Di Natale, M., Musmarra, D., Santonastaso, F. G., Tzatchkov, V., & Alcocer-Yamanaka, V. H. (2015). Dual-use value of network partitioning for water system management and protection from malicious contamination. *Journal of Hydroinformatics*, 17, 361–376. doi:10.2166/hydro.2014.014
- Ezell, B. C. (2007). Infrastructure vulnerability assessment model (I-VAM). *Risk Analysis*, 27, 571–583. doi:10.1111/j.1539-6924.2007.00907.x
- Giustolisi, O., Laucelli, D., & Colombo, A. F. (2009). Deterministic versus stochastic design of water distribution networks. *Journal of Water Resources Planning and Management*, 135: 2, 117–127. doi:10.1061/(ASCE)0733-9496135
- Gleick, P. H. (1993). Water and conflict: Fresh water resources and international security. *International Security*, 18, 79–112. doi:10.2307/2539033
- Gleick, P. H. (2006). Water and terrorism. *Water Policy*, 8, 481–503. doi:10.2166/wp.2006.035
- Haimes, Y. Y., & Horowitz, B. M. (2004). Adaptive two-player hierarchical holographic modeling game for counterterrorism intelligence analysis. *Journal of Homeland Security and Emergency Management*, 1, 1547–7355. doi:10.2202/1547-7355.1038
- Haimes, Y. Y., Matalas, N. C., Lambert, J. H., & Jackson, B. A. (1998). Vulnerability of water supply systems to attack. *Journal of Infrastructure Systems*, 4(4), 164–177. doi:10.1061/(ASCE)1076-0342
- Hickman, D. C. A chemical and biological warfare threat: USAF water systems at risk. The counter proliferation papers future warfare series no. 3. Retrieved from <http://www.au.af.mil/au/awc/awcgate/cpc-pubs/hickman.htm>
- HSPDs. (2002). Public health security and bioterrorism preparedness and response, act of 2002 (Bioterrorism Act). Retrieved from <https://www.gpo.gov/fdsys/pkg/STATUTE-116/pdf/STATUTE-116-Pg594.pdf>
- HSPDsHemeltoday News. (2006). Water spiked with weed-killer. Retrieved from <http://www.hemeltoday.co.uk/news/water-spiked-with-weed-killer-1-1188459>

- Il Giornale. (2017). L'ultima frontiera del terrore: L'Isis userà le armi chimiche. Retrieved from <http://www.ilgiornale.it/news/politica/lultima-frontiera-terrore-lisis-user-armi-chimiche-1347316.html>
- Ilker, A., Ahmet, K., & Ahmet, F. O. (2010). Fuzzy integrated vulnerability assessment model for critical facilities in combating the terrorism. *Expert Systems with Applications*, 37, 3561–3573. doi:10.1016/j.eswa.2009.10.035
- Istituto Superiore di Sanità. (2005). Security of water systems (Reports 05/4 IstiSan). Retrieved from <http://www.iss.it/binary/publ/publi/05-4.1118133781.pdf>
- Maiolo, M., & Pantusa, D. (2015). A methodological proposal for the evaluation of potable water use risk. *Water Practice & Technology*, 10(1), 152–163. doi:10.2166/wpt.2015.017
- Maiolo, M., & Pantusa, D. (2016). An optimization procedure for the sustainable management of water resources. *Water Science and Technology: Water Supply*, 16(1), 61–69. doi:10.2166/ws.2015.114
- Maiolo, M., & Pantusa, D. (2017a). A proposal for multiple reuse of urban wastewater. *Journal of Water Reuse and Desalination* (in press). doi:10.2166/wrd.2017.144
- Maiolo, M., & Pantusa, D. (2017b). Combined reuse of wastewater and desalination for the management of water systems in conditions of scarcity. *Water and Ecology*, 72(4), 116–126. doi:10.23968/2305-3488.2017.22.4.116-126.
- Maiolo, M., Mendicino, G., Pantusa, D., & Senatore, A. (2017). Optimization of drinking water distribution systems in relation to the effects of climate change. *Water*, 9(10), 803. doi:10.3390/w9100803
- Murray, R., Janke, R., & Jim, U. (eds.). (2004, June–July). The threat ensemble vulnerability assessment (TEVA) program for drinking water distribution system security. Proceedings of the World Water and Environmental Resources Congress 2004 (pp. 482–489). Salt Lake City: ASCE Library.
- NSTAC. (1997). Information assurance task force risk assessment. Retrieved from [https://www.dhs.gov/sites/default/files/publications/Information%20Infrastructure%20Group%20Report\\_1997.pdf](https://www.dhs.gov/sites/default/files/publications/Information%20Infrastructure%20Group%20Report_1997.pdf)
- Nilsson, K. A., Buchberger, S. G., & Clark, R. M. (2005). Simulating exposures to deliberate intrusions into water distribution systems. *Journal of Water Resources Planning and Management*, 131(3), 228–236. doi:10.1061/(ASCE)0733-9496
- Panguluri, S., Phillips, W., & Cusimano, J. (2011). Protecting water and wastewater infrastructure from cyber attacks. *Frontiers of Earth Science*, 5(4), 406–413. doi:10.1007/s11707-011-0199-5
- Saaty, T. L. (1980). *The analytic hierarchy process*. New York, NY: McGraw-Hill.
- Saaty, T. L., & Vargas, L. G., (2012). *Models, methods, concepts & applications of the analytic hierarchy process. International series in operations research & management science*. New York, NY: Springer Science Business Media.
- Samani, H. M. V., & Mottaghi, A. (2006). Optimization of water distribution networks using integer linear programming. *Journal of Hydraulic Engineering*, 132(5), 501–509. doi:10.1061/(ASCE)0733-9429
- Sun, W., & Zeng, Z. (2012). City optimal allocation of water resources research based on sustainable development. *Advanced Materials Research*, 446–449(1), 2703–2707. doi:10.4028/www.scientific.net/AMR.446-449.2703
- Tgcom24. (2016). L'Isis vuole avvelenare l'acqua. Retrieved from [http://www.tgcom24.mediaset.it/mondo/turchia-secondo-gli-007-di-istanbul-l-isis-vuole-avvelenare-l-acqua-\\_2155832-201602a.shtml](http://www.tgcom24.mediaset.it/mondo/turchia-secondo-gli-007-di-istanbul-l-isis-vuole-avvelenare-l-acqua-_2155832-201602a.shtml)
- The Times of India. (2010). Maoists poison pond close to CRPF camp. Retrieved from <http://timesofindia.indiatimes.com/india/Maoists-poison-pond-close-to-CRPF-camp/articleshow/6898493.cms>
- The Washington Times. (2003). Al Qaeda warns of threat to water supply. Retrieved from <http://www.washingtontimes.com/news/2003/may/28/20030528-102548-4938r/>
- Thomas, N. (2006). Risk assessment methods for water infrastructure systems. Kingston: Rhode Island Water Resources Center, University of Rhode Island. Retrieved from <http://egr.uri.edu/wp-uploads/wrc/Risk-Assessment-Methods-for-Water-Infrastructure-Systems-2005.pdf>
- Tidwell, V. C., Cooper, J. A., & Silva, C. J. (2005). Threat assessment of water supply systems using markov latent effects modeling. *Journal of Water Resources Planning and Management*, 131(3), 218–227. doi:10.1061/(ASCE)0733-9496
- UPI. (2006). Strychnine found in Danish reservoir. Retrieved from <http://www.upi.com/Strychnine-found-in-Danish-reservoir/34481160165538/>
- US EPA. (2003). U.S. environmental protection agency response protocol toolbox: Planning for and responding to drinking water contamination threats and incidents. Retrieved from [https://www.epa.gov/sites/production/files/2015-06/documents/response\\_protocol\\_part\\_1.pdf](https://www.epa.gov/sites/production/files/2015-06/documents/response_protocol_part_1.pdf)
- US EPA. (2007). U.S. environmental protection agency water security initiative: Interim guidance on planning for contamination warning system deployment. EPA 817-R-07-002. Retrieved from <https://nepis.epa.gov>
- US EPA. (2009). U.S. environmental protection agency national primary drinking water regulations. EPA 816-F-09-004. Retrieved from <https://www.nrc.gov/docs/ML1307/ML13078A040.pdf>
- US EPA. (2010). U.S. environmental protection agency assessing potential impacts associated with contamination events in water distribution systems: A sensitivity analysis. EPA/600/R-10/061. Retrieved from [https://cfpub.epa.gov/si/si\\_public\\_record\\_report.cfm?dirEntryId=224308](https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=224308)
- US EPA. (2015). *Conduct a drinking water or wastewater utility risk assessment*. Office of Water, U.S. Environmental Protection Agency Office of Ground Water, and U.S. EPA Office of Drinking Water. Retrieved from <https://www.epa.gov/waterriskassessment>
- WSAZ News. (2008). *Man accused of threatening water supply*. Retrieved from <http://www.wsaz.com/news/headlines/31232684.html>



© 2018 The Author(s). This open access article is distributed under a Creative Commons Attribution (CC-BY) 4.0 license.

You are free to:

Share — copy and redistribute the material in any medium or format

Adapt — remix, transform, and build upon the material for any purpose, even commercially.

The licensor cannot revoke these freedoms as long as you follow the license terms.

Under the following terms:

Attribution — You must give appropriate credit, provide a link to the license, and indicate if changes were made.

You may do so in any reasonable manner, but not in any way that suggests the licensor endorses you or your use.

No additional restrictions

You may not apply legal terms or technological measures that legally restrict others from doing anything the license permits.



**Cogent Engineering (ISSN: 2331-1916) is published by Cogent OA, part of Taylor & Francis Group.**

**Publishing with Cogent OA ensures:**

- Immediate, universal access to your article on publication
- High visibility and discoverability via the Cogent OA website as well as Taylor & Francis Online
- Download and citation statistics for your article
- Rapid online publication
- Input from, and dialog with, expert editors and editorial boards
- Retention of full copyright of your article
- Guaranteed legacy preservation of your article
- Discounts and waivers for authors in developing regions

**Submit your manuscript to a Cogent OA journal at [www.CogentOA.com](http://www.CogentOA.com)**

