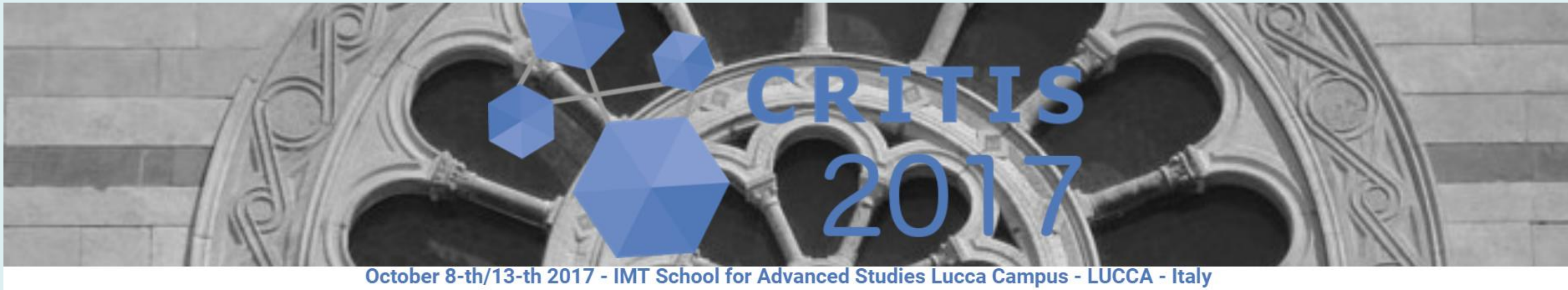

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DMA OPTIMAL LAYOUT FOR PROTECTION OF WATER DISTRIBUTION NETWORKS FROM MALICIOUS ATTACK

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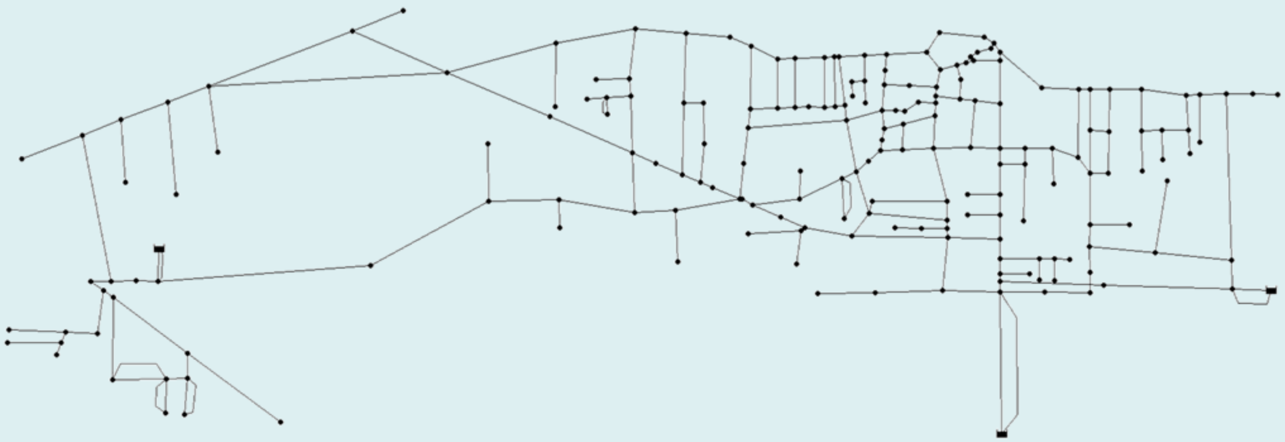
MAIN GOAL

Studying the impact of an intentional contamination attack to Water Distribution Network and a possible strategy to mitigate the risk through the definition of an optimal District Metered Areas layout that take into account also the minimum service level for the users



FURTHER AIMS:

- Valuating the feasibility of adopting Spectral Clustering for the definition of the sub-regions;
- Valuating the dual-use of the Water Network Partitioning on a real water system;
- Investigating the possibility to identify *a priori* the most critical insert points for a contamination in a water distribution network through a topological metric.

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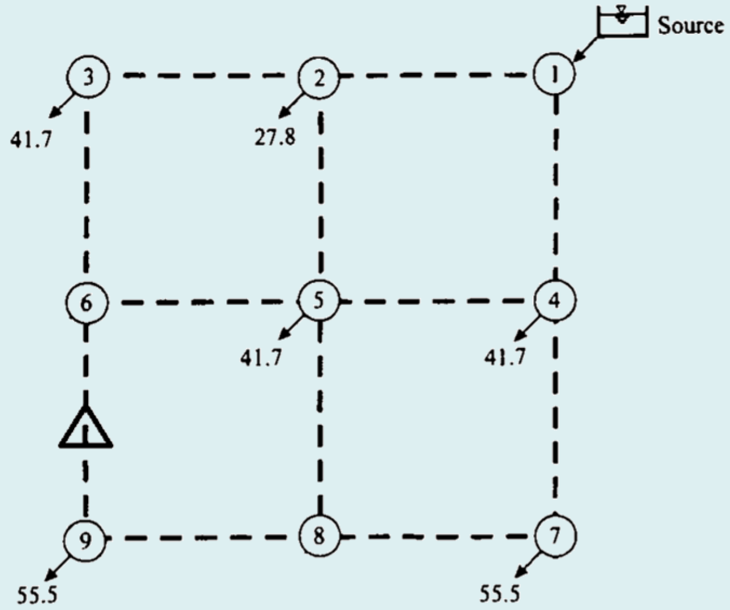
WATER INFRASTRUCTURES

Water Distribution Networks (WDNs) are among the most important civil networks because they deliver drinking and industrial water to metropolitan areas, supporting economic prosperity and human life. Generally they are arranged in large networks and show complex behaviour that needs to be modelled.



Water Distribution Networks (WDNs) can be considered as complex infrastructure, and modelled as a multiple interconnected link-node, spatially organized, weighted graph G=(V,E) where:

- *V* is the set of *n* nodes, pipe intersections, water sources and nodal water demands; and
- *E* is the set of *m* links, pipes and valves.

They belong to the class of networks with real physical connections and strong geographical-economic constrains. Generally the graphs are considered undirected and weighted, where weights express the strength of the link (Diameter, Length, Resistance, Conductance, etc.).

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CRITICAL WATER INFRASTRUCTURES

Water Distribution Networks (WDNs) constitute critical infrastructures **(CIs)** as systems whose operability are of crucial importance to ensure social survival and welfare. Generally global safeguard of systems can not be ever performed against natural or man-made disasters. In this regard, critical infrastructure protection **(CIP)** strategies should be focused on the procedures for the functioning recovery and damage limitation.

WDNs are exposed to different potential sources of contamination:

- ***Accidental contaminations*** are related to occasional bad source water quality, malfunctioning chlorine stations, pipe breaks, and leak repairs;
- ***Intentional contaminations*** are represented by the intentional introduction of a contaminant through a backflow attack that occurs when a pump system is utilized to overcome the local pressure at the insertion point.

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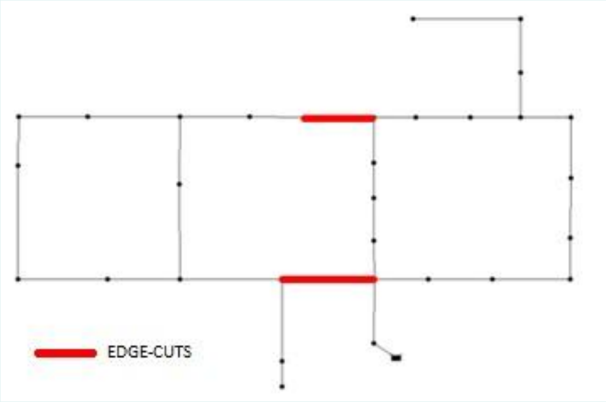
WATER INFRASTRUCTURE PROTECTION

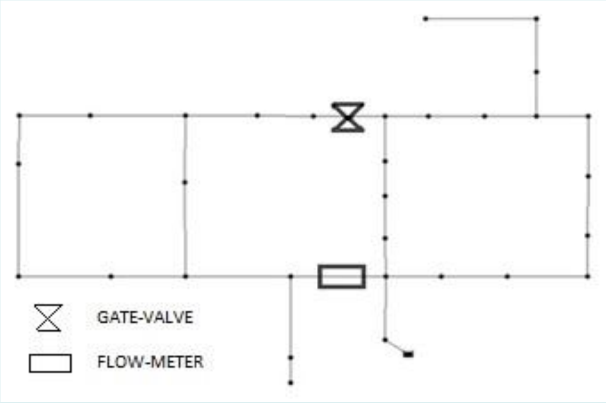
An effective way to limit the damages after a WDN contamination is to close the sector of the network to limit health risks; the effectiveness of this action depends on the possibility of closing pipes and disconnecting network sub-region.

In this regard **Water Network Partitioning (WNP)** shows to be an efficient protection strategy; it is generally obtained in two phases:

- ***Clustering,*** aimed at defining the number, the shape, the dimension of the sub-regions ***k***, with the aim to minimize the edges between clusters, and balance the number of nodes of the clusters;



- ***Dividing***, consists in the selection of pipes on which insert gate-valves or flow-meters, minimizing the investment cost and the hydraulic deterioration and preserving the network continuity.



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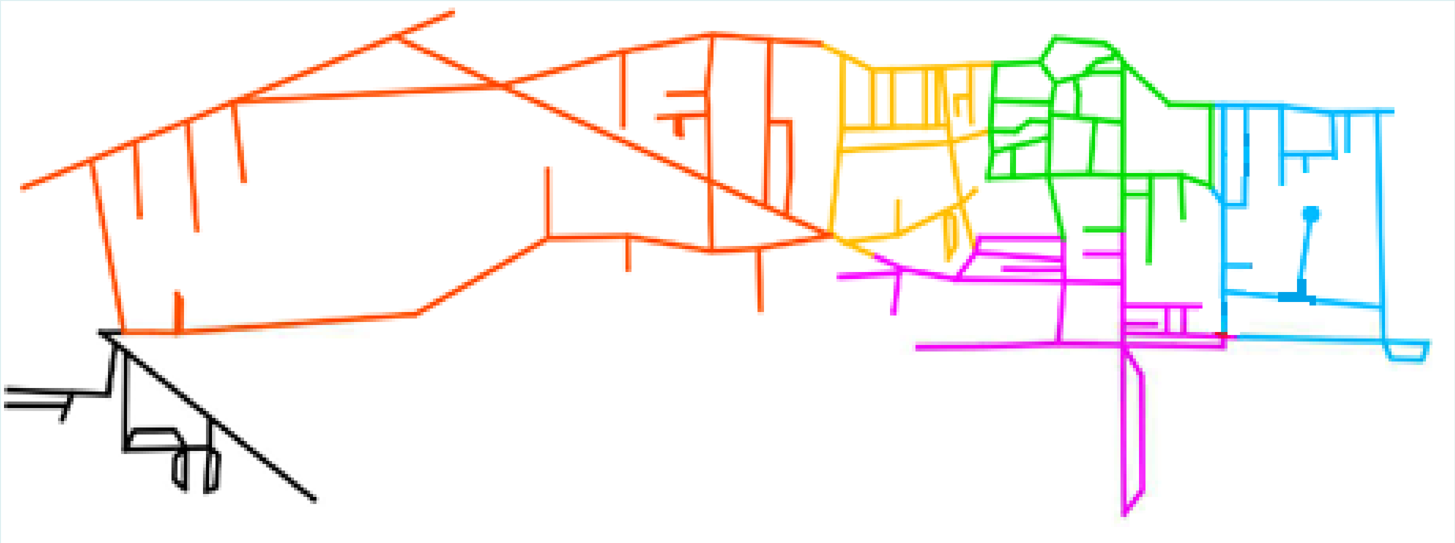
WATER INFRASTRUCTURE PROTECTION

The **Water Network Partitioning (WNP)** shows to be useful also because:

- ✓ It is an effective methodology to improve management by reducing the network complexity;
- ✓ It simplifies the water budgets computation (consequently the identification and reduction of water losses);
- ✓ It simplifies the network maintenance and the pressure control;
- ✓ It reduces the extent of the risk because several introduction points are needed to produce a wide negative impact on the whole network.



Partitioned Network Layout

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METHODOLOGY

Phase 1 Malicious Attack Modeling:

The malicious contamination uses the back-flow attack methodology; potassium cyanide is introduced into the water system through a single point (could be a bathroom tub of a house) by overcoming the local pressure.
The malicious attack is carried out in two times:

- from 7.00 am to 8:00;
- from 9.00 am to 10:00 am.

The lethal concentration of potassium cyanide in water for a user whose bodyweight is 70 kg is 200 mg/l, and the backflow attack was simulated by means of water quality simulation module of EPANET 2.

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METHODOLOGY

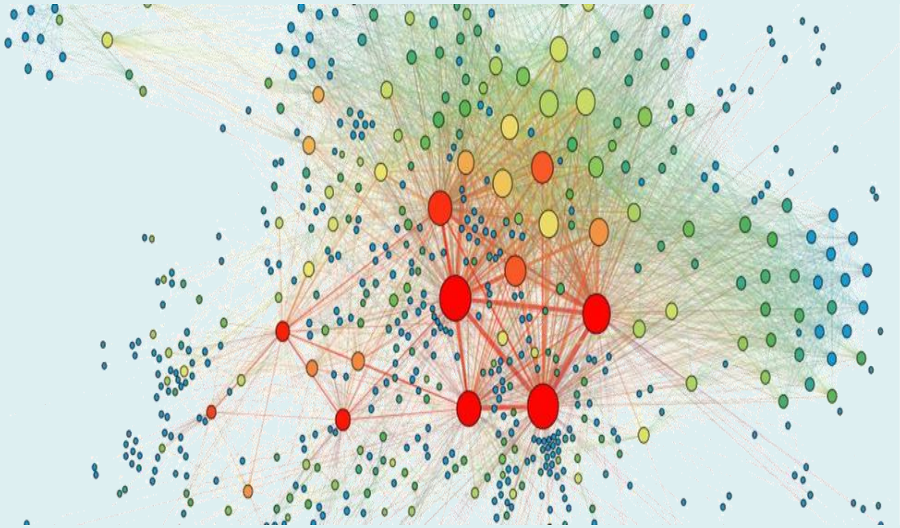
Phase 2 Critical Point Identification:

The most critical insertion points in terms of negative effects for the users are measured as:

- the total number of exposed users (N_{eu})
- the number of exposed users that ingest more than the lethal dose LD_{50} (N_{eu50}), and
- the length of contaminated pipes L_{ep}

and are computed in two different way:

- through a full analysis of all possible positioning of a malicious attack in the network;
- through the computation of the weighted ***eigenvector centrality*.**



The ***Eigenvector Centrality***, a topological local metric, is a good measure of node-centrality; for each node, it corresponds to the component value of the principal eigenvector of the Adjacency matrix A of the water network graph according to the principle **"I am influential if I have influential friends"**

In order to take into account also hydraulic aspects, the network graph was considered undirected and weighted with the pipe flow.

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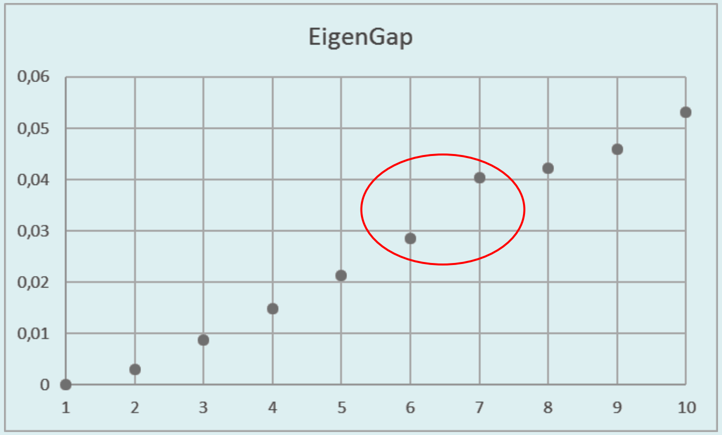
METHODOLOGY

Phase 3 Water Network Clustering:

the aim is to provide a clusters layout that simultaneously minimize the number of boundary edges and balance the number of nodes in each cluster.

SPECTRAL CLUSTERING:

- The proper number of clusters was defined through the ***Eigengap***, and so six clusters were chosen as optimal number of sub-regions;



- The normalized spectral clustering algorithm ***Ncut*** based on the spectrum of the graph Laplacian matrix is used to define the shape and the dimension of the clusters.

$$Ncut(A_1,\ldots A_k) = \sum_{i=1}^{k} \frac{cut(A_i, \overline{A_i})}{vol(A_i)}$$

Compute the first k generalized eigenvectors of the generalized eigenproblem

Lu = λDu.

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METHODOLOGY

Phase 4 Water Network Dividing:

The clustering phase provides the set $\boldsymbol{N_{ec}}$ of boundary pipes along which flow meters and gate valves must be installed.

-The number of flow meters is fixed as low as possible

-The number of all possible $\boldsymbol{N_c}$ device positioning combination is expressed by Binomial Coefficient:

$$N_C = \binom{N_{ec}}{N_{fm}}$$

An optimization technique was developed in order to find the optimal device positioning on the boundary pipes, maximizing the constrained Objective Function “Total Node Power”:

$$OF = \max \gamma \sum_{i=1}^{n} Q_i H_i$$

where Q_i and H_i are the water demand and the hydraulic head of the *i-th* node, and the constrain is

$$h_{min} > h^*$$

where h_{min} is the minimum pressure and h^* is the design pressure required to satisfy water request

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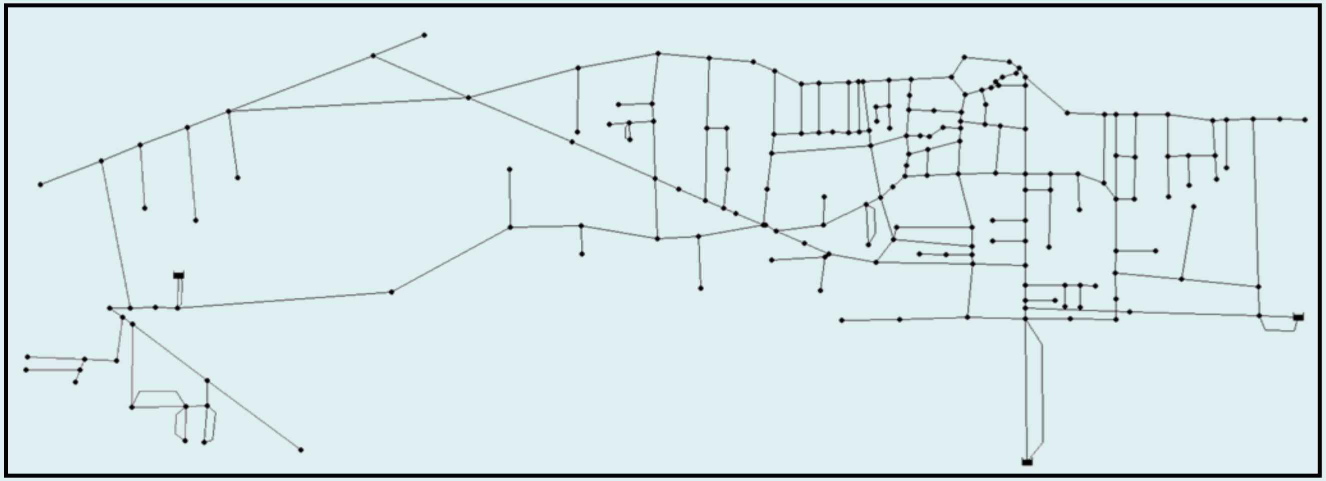
CASE STUDY

Real medium-size Water Distribution Network serving the town of Villaricca, located near Naples (Italy), with about 30,000 inhabitants. The Water Distribution Network has three source and its main hydraulic characteristics are reported below:



n [-]	m [-]	n_r [-]	L_{pToT} [km]	h_{min} [m]	h_{mean} [m]	h_{max} [m]	h^* [m]
196	249	3	34.71	25.11	36.54	45.94	25.00

The hydraulic performances of the are good in terms of nodal pressure head since they higher than the design pressure head h*=25m that is fulfilled in the whole system.

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RESULTS

Most critical Point:

The first 5 most critical points are reported computed in terms of the negative impact measured by N_{eu50}. In this case study, and with a pipe weight equal to water flow, only the node **104** is in both sets.

Water Quality simulation	Weighted Eigenvector centrality
104	145
159	100
126	141
127	104
19	78

Additional information about the worst nodes as insertion point, cyanide concentrations, and other simulation details are not reported for evident safety reasons.

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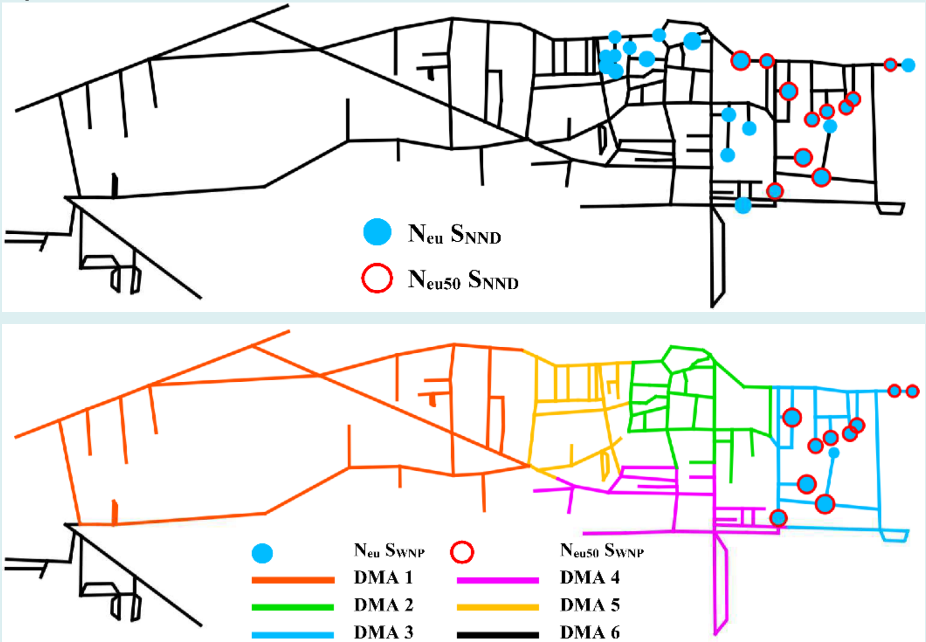
RESULTS

Effectiveness of water network partitioning :

The water network was divided in 6 District Meter Areas (DMAs) fixing the number of flow meters N_{fm}=6, which is the minimum possible number that guarantees the hydraulic performance of the network.



Contamination layout for un-partitioned and partitioned WDN of Villaricca

Network	N_{eu} [-]	N_{eu50} [-]	L_{ep} [m]
S_{WDN}	9,970	5,063	13,906
S_{OWNP}	4,258	4,078	8,112

Contamination results for un-partitioned and partitioned WDN of Villaricca

The results show a significant reduction of ***N_{eu}* (about 57%),** a less (but also important) reduction of ***N_{eu50}* (about 20%)** and a reduction o total contamination length, ***L_{ep}* (about 42%)**

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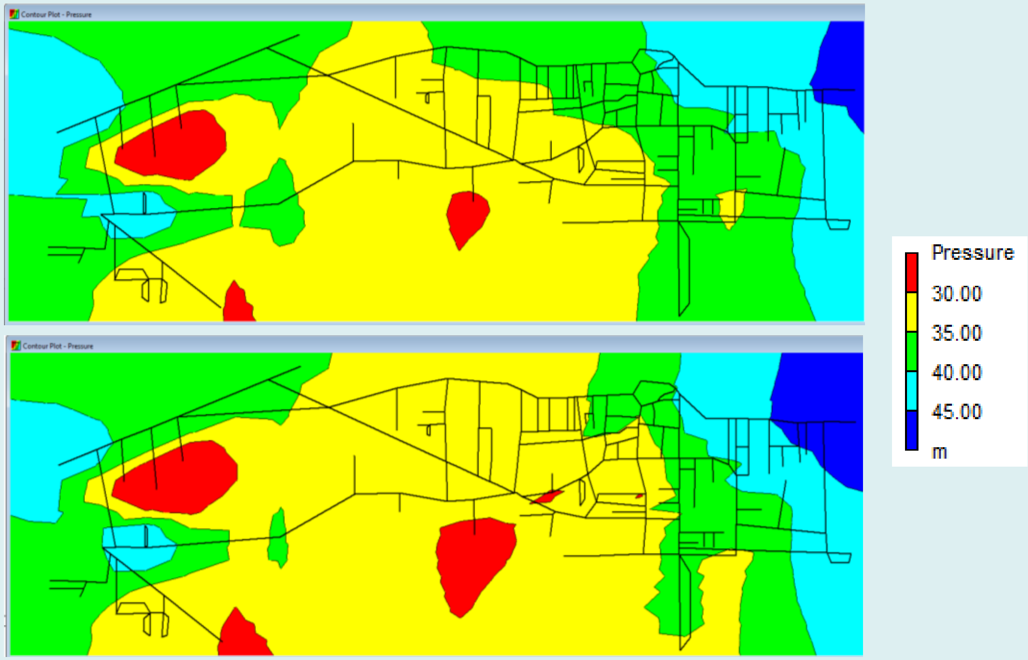
RESULTS

Effectiveness of water network partitioning :

The hydraulic performance of the partitioned water network shows that they are preserved with a slight reduction of the level of service for the users.



Pressure layout for un-partitioned and partitioned WDN of Villaricca

h_{min} [m]	h_{mean} [m]	h_{max} [m]	I_R [-]
25.11	36.54	45.94	0.524

Hydraulic performance of un-partitioned WDN

h_{min} [m]	h_{mean} [m]	h_{max} [m]	I_R [-]
25.42	35.23	47.78	0.462

Hydraulic performance of partitioned WDN

The results show a less reduction of the hydraulic performance in particular for ***I_R* is about 12%** that means that the global energy resilience of the system is preserved

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RESULTS

Effectiveness of water network sectorization :

The study also analyses different scenarios consisting into the total isolation of the contaminated DMA in the case of closure after 1 hour of the malicious attack and after 3 hours and with source corresponding to the most critical point of each DMA.

DMA Isolation	N_u [-]	N_{eu} [-]	N_{eu50} [-]	L_{ep} [m]
S_{WNS1}	7,930	3,134	0	5,072
S_{WNS2}	8,042	569	0	5,508
S_{WNS3}	4,258	3,222	0	4,468
S_{WNS4}	5,539	3,604	0	4,533
S_{WNS5}	4,955	1,803	0	4,720
S_{WNS6}	570	161	92	1,612

Simulation results for each WNS scenario of Villaricca with DMA closure at 08.00 am

DMA Isolation	N_u [-]	N_{eu} [-]	N_{eu50} [-]	L_{ep} [m]
S_{WNS1}	7,930	3,497	1,014	7,495
S_{WNS2}	8,042	5,519	2,196	6,162
S_{WNS3}	4,258	4,078	788	7,983
S_{WNS4}	5,539	3,604	676	4,923
S_{WNS5}	4,955	3,605	788	7,604
S_{WNS6}	570	455	455	3,068

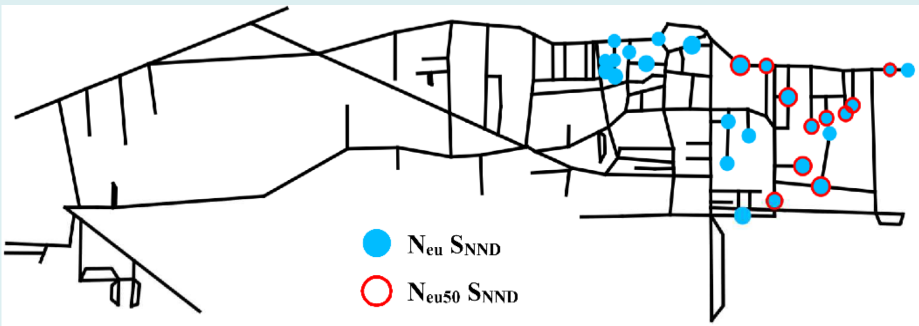
Simulation results for each WNS scenario of Villaricca with DMA closure at 10.00 am

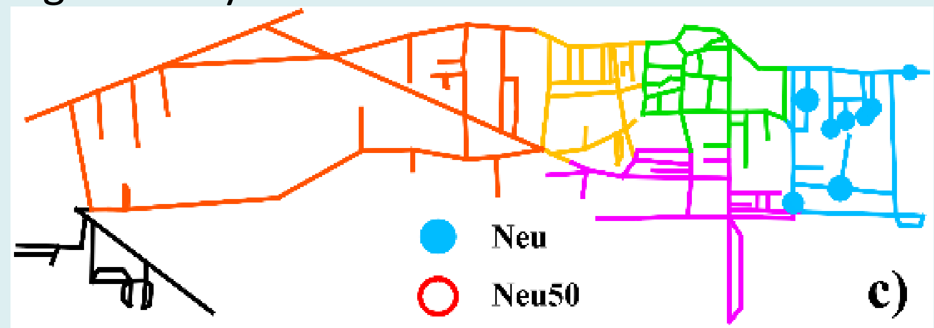
The early warning system, allowing the closure of the corresponding district after an 1 hour from the beginning of the malicious attack, provides an almost total protection of the network in terms of N_{eu50}. Also with a larger delay in the early warning, the simulation results are good

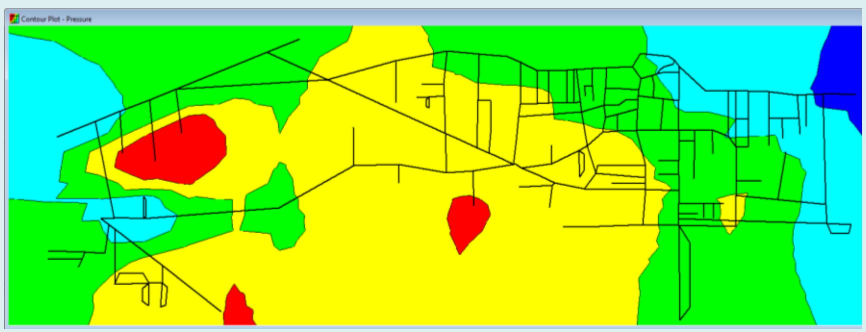
RESULTS

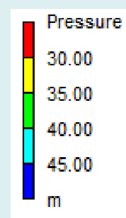
Effectiveness of water network sectorization :

It is evident that the contaminated users are significantly lower









Contamination and pressure layout for the un-partitioned WDN of Villaricca

h_{min} [m]	h_{mean} [m]	h_{max} [m]	I_R [-]
25.11	36.54	45.94	0.524

Contamination and pressure layout for the WDN of Villaricca with the isolation of the DMA3

h_{min} [m]	h_{mean} [m]	h_{max} [m]	I_R [-]
21.78	32.52	48.22	0.334

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CONCLUSIONS

- ✓ The paper presents a strategy for the **risk mitigation of a malicious attack** to a real Water Distribution Network;
- ✓ The **partitioning** of the network confirms the effectiveness in mitigating the effect of a contamination attack preserving the hydraulic performances simultaneously
- ✓ The results confirm the effectiveness of the **spectral clustering** in providing sub-regions layout, balanced and with a low number of edge-cuts
- ✓ The **weighted eigenvector centrality** shows to be a valid tool for the definition of the "most influential" nodes but further studies are needed
- ✓ An *a priori* definition of the most important nodes could also simply the arduous problem of optimal **sensor placement** and efficient monitoring
- ✓ Further studies are needed to improve and generalize the methodology

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Thank you for the attention