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Natural hazard risk analysis in the framework of water safety plans

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ABSTRACT

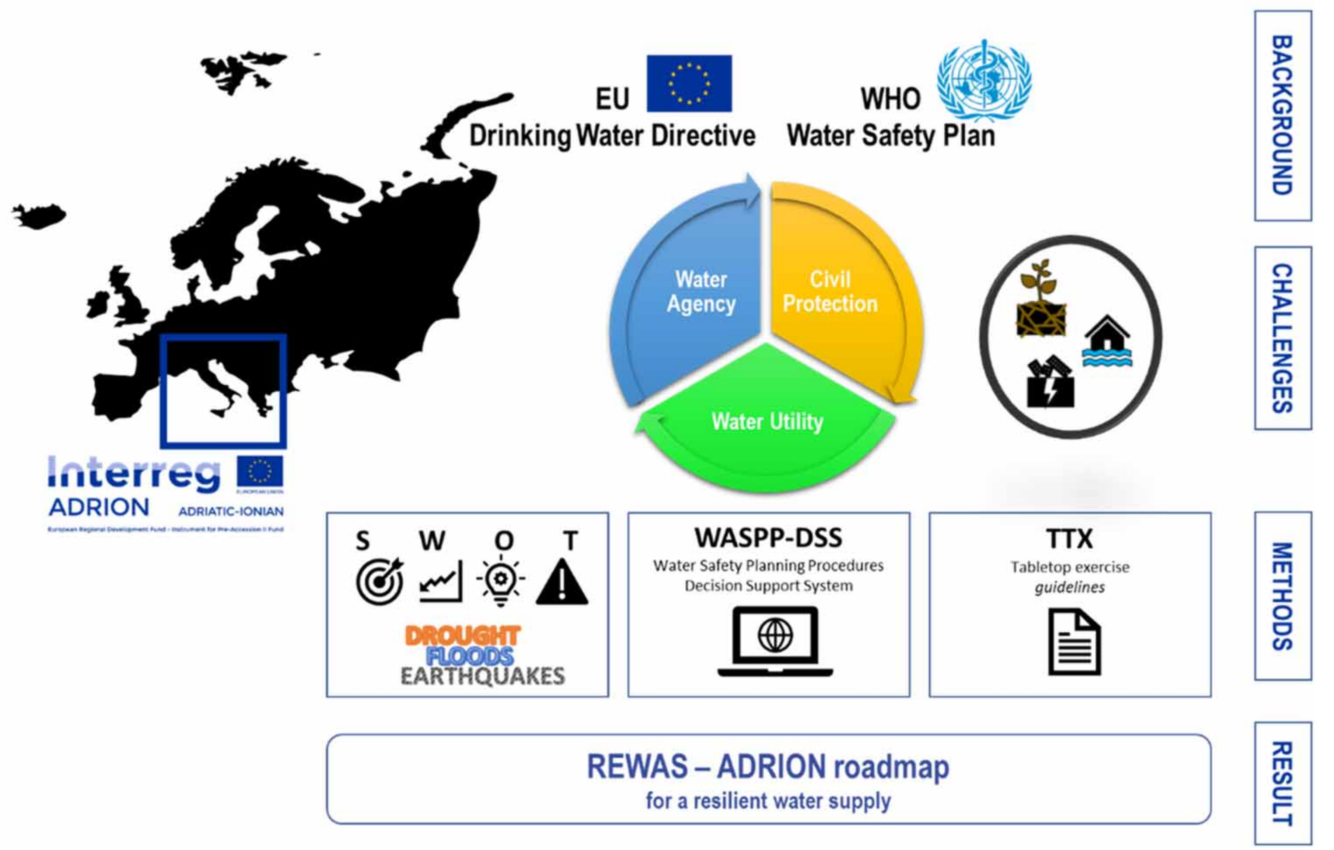
The available literature on natural hazard risk analysis focused on the implementation of water safety plans (WSPs) is surprisingly quite poor, despite the significant increase in the number and severity of disasters and adverse effects on drinking water supply systems generated by natural hazards. At the same time, WSPs that conveniently account for natural hazards with a comprehensive approach 'from source to tap' are still scarce as they typically occur at larger spatial scales and adequate prevention, mitigation and adaptation require efficient inter-institutional collaborations. The aim of this paper is to highlight the main bottlenecks for water utilities to include natural hazards in the development of their WSPs. The research adopted a stakeholders-oriented approach, involving a considerable number of water utilities (168), water sectoral agencies (15) and institutions (68) across the Adriatic-Ionian Region through a stepwise process that generated joint SWOT analysis, the development of a decision support system (DSS) focused on WSPs procedures and tabletop exercises. The final outcomes generated strategic documents (REWAS – Adrion Road map for resilient water supply) that highlighted the necessity for efficient cross-sectoral and inter-institutional cooperation in the development of well-founded and robust WSPs to address natural hazard risk analysis for water supply systems (DWSS).

Key words: civil protection mechanism, EU drinking water directive, multihazard risk assessment, water safety plan, water utilities

HIGHLIGHTS

- Development of water safety plans accounting for natural hazards is challenging.
- A detailed SWOT analysis on bottlenecks limiting effective risk analyses for WSPs is here presented.
- Guidelines for tabletop exercises focused on the development of WSPs are proposed.
- Evidence-based suggestions to overcome issues related to natural multihazard risk analysis for WSPs are here presented through specific strategic documents.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The right to safe and clean drinking water and sanitation is recognized as 'a human right that is essential for the full enjoyment of life and all human rights' (UN 2010). The European Union defined key standards for drinking water supply with the EU Drinking Water Directive 2020/2184 (EU 2020) whose main objective is 'to protect human health from the adverse effects of the contamination of water intended for human consumption by ensuring that it is wholesome and clean, and to improve access to water intended for human consumption'. The directive recommends the 'Water Safety Plans' (WSPs), 'a comprehensive risk assessment and risk management approach that encompasses all steps in water supply from catchment to consumer' (WHO 2009) as the suitable and effective tool for drinking water utilities to provide constantly safe drinkable water. Although the drinking water supply systems (DWSSs) have (or should have) disaster risk management and contingency management plans, the single-hazard approach is prevailing. Thus, alternatives are single-hazard approaches, which do not integrate in the best way all relevant information, data and sectors. In addition, there are river basin management plans, flood risk management plans and drought management plans, but drinking water sources are only a part of water management. The comprehensive approach of the WSPs adopts a multihazard perspective and requires, as a consequence, the involvement of different sectors and institutions, regional and local administration, civil protection systems, water agencies and water utilities.

The risks associated with hydroclimatic extreme event hazards and how to improve the resilience of water supply services to cope with these weather conditions only recently started to be addressed in the contest of the WSPs. The Second Edition of the Water Safety Plan manual (WSPM 2023 hereafter) (WHO 2023) specifies that robust water safety planning must consider the vulnerability of the water supply to current and future impacts from climate variability and change. More generally, natural hazards (not only related to climate variability and change) should be explicitly considered in several modules of a WSP to ensure effective risk management through the WSP development process. Indeed, within the general framework of management and emergency planning, an integration and harmonization of the different operational levels, from the transboundary and national levels to the local ones is mandatory and usually very difficult to reach (WHO 2017).

The scientific literature on natural hazard risk analysis specifically dedicated to WSPs development and implementation is surprisingly quite poor, despite the significant increase in frequency and severity of natural hazards in recent years that adversely affected DWSSs.

Tsoukalas & Tsitsifli (2018) grouped the main benefits and difficulties related to the implementation of WSPs in Europe, and stressed limitation factors for successful implementation of WSPs such as the lack of legislation, and inappropriate monitoring systems in place; limited experience of its staff; the difficulty in assessing all potential hazards; and the lack of supporting activities. These limitations appear to exacerbate the difficulties in developing and implementing robust and effective WSPs especially when considering natural hazards such as droughts, earthquakes and floods, which typically occur at basin (catchment) scale or even larger.

With respect to floods, a number of specific studies were dedicated to the main impacts on DWSSs (from source to tap): quality degradation in both groundwater resources (Joannou *et al.* 2019; Sweya & Wilkinson 2020) and artificial reservoirs (Chou & Wu 2010); damages to infrastructures (Arrighi *et al.* 2017) and treatment facilities (Barnes *et al.* 2012; See *et al.* 2017). Several studies evaluated earthquakes' impacts on water supply systems (Mishra 2018; Bata *et al.* 2022; Pagano *et al.* 2022). Increasing interest has recently been given to approaches that assess the vulnerability of the water distribution network (i.e., distribution infrastructures), independently from the triggering hazard (Yazdani & Jeffrey 2012; Agathokleous *et al.* 2017; Pagano *et al.* 2018; Shuang *et al.* 2019). Concerning drought, the main issue is how to frame such a hazard in the context of WSPs, given the multiple triggers (i.e., precipitation deficit along with possible high temperatures) are clearly far beyond the scale of the DWSSs, really claiming for a comprehensive approach, able to analyse the DWSS as a whole (Diao *et al.* 2016; Serio *et al.* 2021).

Risks related to floods and droughts in the context of the DWSSs are even exacerbated by climate change, as strongly stressed in WSPM (2023). Although this issue is urgent, there are a small number of experiences that include climate change in WSPs. The literature review compiled by Rickert *et al.* (2019) summarizes the global experience on WSPs including climate change. Considering the period between 2010 and 2018, the review indicated that limited information has been published on how to integrate climate change aspects into a WSP: a few selected countries of the WHO regions Africa, Europe, Southeast Asia and the Western Pacific, meanwhile some regions are still neglected and globally more work is required. As the world is experiencing situations with more extreme and complex calamitous events, with far-reaching and long-term consequences, an integrated approach to disaster management becomes increasingly important (Amarasinghe *et al.* 2017; Rodriguez-Alvarez *et al.* 2022), especially for medium-term horizons.

The main goal of this paper is to introduce the framework for multihazard risk assessment integration in the WSPs. The presented research is based on the MUHA project – 'MUltiHAzard framework for water-related risks management' (INTERREG V-B Adriatic-Ionian ADRION 2014–2020 Programme) activities implemented by institutions from Italy, Slovenia, Croatia, Serbia, Montenegro and Greece. The MUHA project (MUHA 2023) aimed at connecting four hazards (droughts, floods, earthquakes and accidental pollution) and related risks to the integrated drinking water system management (water utilities and water agencies) with the civil protection mechanisms on a national, international and EU level in the overall framework of the WSPs. This paper focuses on the three natural hazards among those considered in the project (i.e., droughts, floods and earthquakes).

The MUHA project stakeholders-oriented approach involved diverse water utilities (168), water sectoral agencies (15) and public authorities (22 national, 24 regional and 22 local) within the project scope area in all phases of tools and outputs development. The main objective of this work is to propose a strategic document that highlights the main issues related to natural hazard risk analysis in the framework of WSPs and suggests some lines of interventions mainly aimed at fostering interagency cooperation for resilient water supply management. The main pillars (described in detail in the Method section) of the work are SWOT analysis, development and testing of the water safety planning procedures decision support system (WASPP-DSS) tool and identification of the bottlenecks and elements of weakness in the actual emergency plans through tabletop exercises (TTXs), whose structure has been specifically developed to this end.

2. METHODS

The overall method adopted to identify the main issues related to natural hazard risk analysis in the framework of WSPs was conceived to support the implementation of the modules suggested by the WHO to develop the plans (WHO 2009). It includes four steps:

1. *SWOT analysis*. A detailed SWOT analysis on the current (2020) status of implementation of the WSPs (section 2.1) was performed with water utilities (WUs) located in six countries of the ADRION area (Italy, Slovenia, Croatia, Serbia, Montenegro and Greece) by means of dedicated questionnaires, interviews and workshops.
2. *WASPP-DSS tool.* The SWOT analysis drove the development of WASPP-DSS, an informative platform, supporting module 2 (*Describe the water supply system*) and module 3 (*Identify the hazards and assess the risks*) of the WHO manual (WHO 2009). Such a tool (section 2.2) addresses the difficulty in assessing all potential hazards and risks and the consequent need to provide WUs with standardized supporting tools.
3. *Tabletop exercises.* Risk analysis (modules 3–4 of the WHO manual) and identification of emergency plans (modules 8–9) in the framework of WSPs require, especially in case of droughts, floods and earthquakes, the involvement of several institutions and stakeholders. We identified the 'tabletop exercise – TTX' as a suitable tool for involving effectively all the actors in the development of a WSP, proposing a detailed structure to perform and evaluate it (section 2.3, SM4 – Guidelines for TTXs in the framework of WSPs and SM5 – Action Plan for the development of TTXs for improved WSP reliability). Outcomes from the TTXs performed in four pilot areas, along with the performed SWOT analysis and the testing phase of the WASPP-DSS, provided several hints for the development of robust and effective WSPs, pinpointing bottlenecks and their possible ways out.
4. *REWAS-ADRION strategic documents.* Feedback from SWOT analysis and TTXs were organized in specific strategic documents for the development of WSPs addressing: (a) water utilities; (b) civil protection authorities; and (c) water authorities. In section 3.4, the priority axes of such strategic documents are presented in detail and further discussed. The complete documents are attached to this paper as Supplementary Material (SM6, SM7 and SM8).

Considering all the methodological steps mentioned earlier, the number of water utilities involved constitutes a very representative percentage in terms of inhabitants supplied: approximately 50% for Italy, 26% for Slovenia, 25% for Serbia, 70% for Montenegro and 40% for Greece. It is worth stressing that all the outcomes presented in the following were extrapolated from the feedback received from the stakeholders. In other words, the authors did not add elements (based for example on their own experience or scientific skills), but organized in a structured way all the information coming from the stakeholders through questionnaires, workshops, interviews, etc.

2.1. SWOT analysis

A detailed SWOT (strengths, weaknesses, opportunities, threats) analysis on the current (2020) procedures for the development of WSPs at the country and WU level was carried out with the aim of identifying internal and external factors actually fostering and limiting the implementation of WSPs. Three natural hazards were considered: droughts, floods and earthquakes. An online questionnaire form was created and sent to WUs and scientific and professional associations located in the ADRION area (Italy: 33; Slovenia: 5; Serbia: 4; Montenegro: 5; Greece: 30), allowing us to identify the current status of implementation of WSPs in the area of interest. It is worth stressing that in 2020, the WSP was developed and finalized by only one WU in the whole area. The received feedback (approximately 25% of the water utilities requested), analysed by the MUHA team, allowed for identifying and grouping the main bottlenecks faced by the water utilities in starting the WSP development. Such an analysis was then deepened by means of interviews (either online or face to face, depending on the stakeholders' availability) addressed to WUs located in specific pilot areas: Ridracoli (Italy), Kamnik (Slovenia), Region of Istria (Croatia), Golubinka (Croatia), Niksic (Montenegro) and Larissa (Greece). In Figure 1, the map of pilot sites (six in total) and the related hazards possibly impacting the water supply systems (WSSs) are shown.

Such two-step analysis (questionnaires + dedicated interviews) allowed the MUHA team to identify the *internal* and *external* factors affecting the preparation of WSPs in real cases. *Internal factors* include existing resources and capabilities within the organization that have control over internal factors such as geographical location, financial resources, technical resources and capabilities, human resources, internal communication, management, and services. *External factors* include opportunities and threats that are outside of the organization which it may be able to influence – or at least anticipate – but not fully control such factors as technology innovations and changes, economic trends, government policies and legislation,

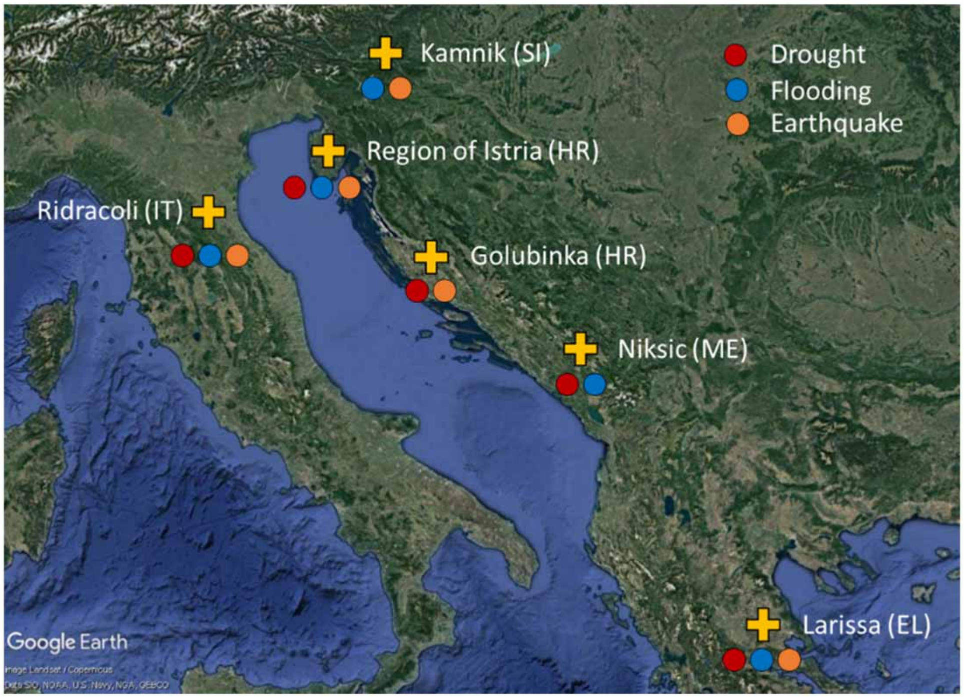


Figure 1 | Map of pilot sites and related hazards impacting WSSs.

legal judgments, and social trends. The performed analysis distinguished a '*national*' level from a '*utility*' level because the internal environment at the country level is the external environment at the utility level. The first level (*national level*) analysis aims to highlight the interlinkages between administrative bodies and stakeholders (central government; ministries, regional and local authorities; and water utilities). The second level (*utility level*) analysis takes into consideration the day-to-day operations of the WUs.

Finally, the preliminary results of the SWOT analysis were shared through a dedicated workshop (either online or in person, depending on the country) held at the national level in each project's country with the project's stakeholders (association of WUs and WUs; water regulators; health authorities; association of local communities; and similar), to get their feedback, for their responses to be incorporated as key messages for the country.

2.2. WASPP-DSS tool

The SWOT analysis highlighted two issues such as the lack of officially recognized common schemes shared by the WUs, and the difficulty of small and medium-sized WUs to implement WSPs. Moving from such analysis, the need for specific tools to support a preliminary but complete screening able to individuate the WSS components prone to specific hazards and to rank hazards and related risks to deliver initial risk matrices, according to the WHO WSP manual became more than obvious (WHO 2009). To this goal, a specific platform, named WASPP-DSS, available at http://muha.apps.vokas.si/home after registration (accessed 22/01/2024), was developed. A short tutorial of the platform can be found at https://www.youtube.com/watch?v=bfHxK3aFgsM (accessed 22 January 2024).

The WASPP-DSS (the reader can refer to Barbetta *et al.* (2022) and Romano *et al.* (2022) for a detailed description of the tool) allows for a first analysis aimed at ranking the hazards and related risks impacting a given WSS. Having a shared scheme of analysis may boost comparison among different WSPs, promoting collaboration among WUs acting in close territories or, in some cases, having interconnections.

The tool supports the development of module 2 (*Describe the water supply system*) and module 3 (*Identify the hazards and assess the risks*) of the WSP manual (WHO 2009). It is basically constituted by a 'catalogue of hazardous events' crossed through a matrix approach by a 'catalogue of water supply system components'. The following components are considered: (1) surface water resources; (2) groundwater resources; (3) artificial recharge; (4) raw water intake; (5) raw water storage and transport; (6) treatment; (7) reservoir and pumps; (8) transport and distribution; (9) internal piping; (10) organization and information; (11) governance and future hazards. Some of these components are in turn split into subcomponents. Each hazardous event is described in a specific box summarizing the related trigger, consequences, and possible measures. The user is required to evaluate the probability of occurrence by selecting an estimated return period among some predefined categories (from weekly to 30 years or more) and the severity of occurrence. The two components are combined to compute a risk estimation, in turn, categorized as very low, low, medium, high and very high. The outcomes are given in terms of the number of hazardous events identified and completed, the number of hazardous events per component and hazard category, the severity of consequences by component and by hazard and the risk category by component and by hazard.

The WASPP-DSS was extensively tested by the 12 WUs listed in Table 1. An online questionnaire form was created and sent to each water utility to get information on the topics listed below.

- Completeness of the 'catalogue of components' included in the tool.
- Completeness of the 'catalogue of hazardous events' included in the tool.
- Assessment of the internal (at the WU level) availability of the data required by the tool.
- Assessment of the external availability of the data required by the tool.
- Assessment of the reliability of the internal/external data acquired to be used as input of the tool.
- Identification of the possible other institutions to be involved in the risk analysis process.
- Robustness of the risk analysis performed, mostly in relation to WSPs.
- Utility of the reporting structure delivered by the tool as output.

The results of the questionnaires allowed us to highlight the strengths and weaknesses of the WASPP-DSS and to point out specific issues in the implementation of WSPs that drove the draft of the strategic documents (section 3.4).

2.3. Tabletop exercises

Usually, WUs do not have defined acts, rules and obligations for cross-border water supply in case of emergencies. Especially, there is no obligation to hold TTXs or practical exercises that simulate hazardous events and, even the ones in place, are currently lacking in the procedures and are not standardized. In a TTX, an artificial environment that reproduces all or part of hazardous event scenarios is simulated. The main goal of a TTX is to test decision-making processes that refer to civil protection plans or existing intervention models.

To bridge the gap among civil protection authorities, water cycle managers and service providers, a methodological approach based on a literature review (FEMA 2003; Direttiva PCM 2021; EU 2021) for performing TTXs was proposed by the Italian Civil Protection Department, a project partner. Starting from the proposed method, discussed and agreed with the entire partnership, a set of guidelines (Table 2) were drafted and subsequently tested in the national pilot areas (three water utilities and one municipality) with the relevant stakeholders (Table 3). A complete version of Table 2, detailing

Table 1 | Water utilities involved in the testing phase of the WASPP-DSS tool

Country	Water utility	Supplied inhabitants
Italy	Romagna Acque – Società delle Fonti	1,100,000 in
	SMAT – Torino	2,200,00 in
	VERITAS – Venezia	800,000 in
Slovenia	Municipality of Kamnik	15,000 in
Croatia	Water utility of Istria for the production and distribution of water	100,000 in
	Water supply company Zadar	110,000 in
Montenegro	Doo "Vodovod and kanalizacija" Nikšić	68,000 in
Serbia	Belgrade PU company 'Water and Sewerage'	1,500,000 in
	Šabac PU company 'Water and Sewerage'	70,000 in
	Regional DWSS 'Rzav'	150,000 in
	Public water supply utility Kikinda	50,000 in
Greece	Municipal Water Supply and Sewerage Company of Larissa	230,000 in

Table 2 | Scheme of the proposed guidelines for TTXs in the framework of WSPs. The detailed version of the guidelines is available in the Supplementary Material (SM4)

Introduction	Planning	Management	Evaluation
The tabletop exercise	Objectives	Staff and team procedures and actions	Report and evaluation
Event and risk scenarios	Team staffing and rules	Training programme	Lessons learned

Table 3 | The pilot areas and related stakeholders involved in the tabletop exercises

			Stakeholders	
Pilot	Country	Hazard	Categories	Number of participants involved in TTX
Romagna Acque – Società delle Fonti, Ridracoli	Italy	Drought	Civil Protection Water Utility Research Institute Municipality and related public services Environmental Protection Agencies Public Health Department Water Management	35
Doo 'Vodovod and kanalizacija', Nikšić	Montenegro	Drought	Civil Protection and Rescue Service Water Utility Water Institute Fire Brigade Citizens	15
Municipality of Kamnik, Kamnik	Slovenia	Floods	Civil Protection Water Utility Municipality and related public services University Water Institute	20
DEYAL, Larissa	Greece	Earthquake	Civil Protection Water Utility Municipality and related public services Region Police Fire Department Electricity Distribution Network Operator Association of the Radio Amateurs (local volunteering organization)	15–20

how to plan and perform a TTX can be found in Supplementary Material (SM4 – Guidelines for TTXs in the framework of WSPs).

After the TTXs were finalized in the pilot sites, each stakeholder participating in the exercise completed the evaluation test. The goal was to evaluate the performance in the preparation and execution phase of the exercise in order to:

- identify the strengths and weaknesses of the system;
- identify if and what are the margins for improvement,
- indicate where to focus more efforts in case of a real event;
- define some 'best practices';
- acquire knowledge on the development of the exercise process thanks to an external point of view.

The evaluation process is summarized below (Figure 2).

The complete evaluation checklist proposals, designed by both the Italian and Greek partners, inspired by guidelines for conducting civil protection exercises (Neiflex exercise 2018; Document with protocol no. 532/23.1.2020 entitled 'Planning,

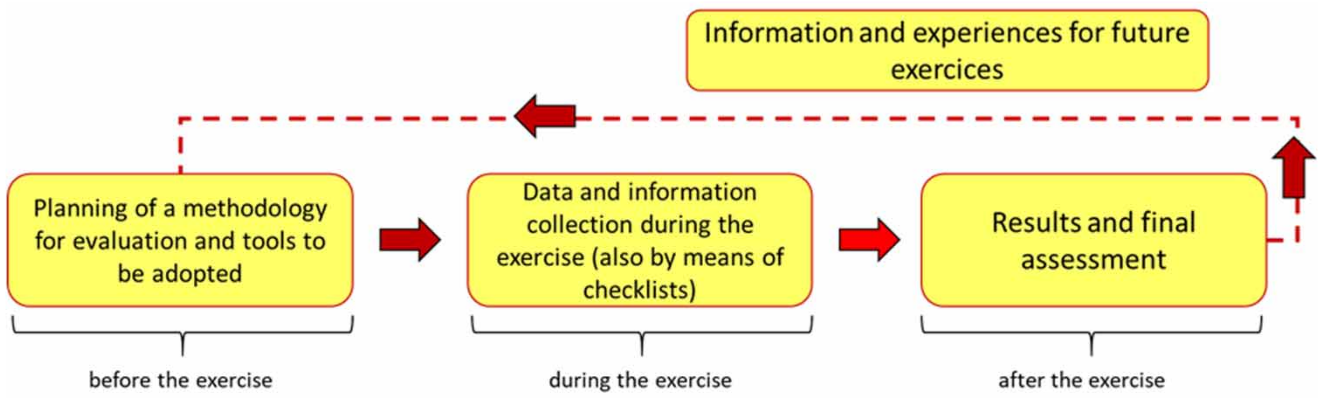


Figure 2 | Outline of the evaluation process of tabletop exercises.

Conduct, and Evaluation of Civil Protection Exercises), are reported in the Supplementary Material (SM4 – Guidelines for tabletop exercises in the framework of WSPs).

The outcomes of the evaluation tests were collected, analysed and discussed among both the TTX participants independently for each pilot and then within the project partnership. The conclusions were used to write the action plan for the development of TTXs for improved WSS reliability (SM5 – action plan for the development of tabletop exercises for improved WSP reliability).

2.4. REWAS-ADRION strategic documents

Results of this work proposed the so-called REWAS-ADRION, a roadmap for a more resilient water supply focused on natural hazards, recognizing the specific involvement of each organization (water utilities, civil protection, water agencies). The goal of the strategic documents is to support water utilities, civil protection organizations and water authorities to identify and mitigate hazardous events, contributing to water supply resiliency by means of the instrument of WSPs. The strategic vision is the enhancement of water supply systems resilience to natural hazardous events, by the improvement of the water safety planning mechanism built on the interagency cooperation concept and in the light of the Revised Drinking Water Directive (EU) 2020/2184 challenges.

The MUHA team analysed the outcomes from the SWOT analysis, from the WASPP-DSS and from the TTXs and preliminarily identified some priority axes of intervention focused on specific targets for robust development and implementation of WSPs and the related strategic actions (practical actions). Discussion with stakeholders in the framework of dedicated workshops held at the national scale led to the final version of the REWAS-ADRION strategic documents summarized in section 3.4 and entirely reported in Supplementary Materials (SM6, SM7 and SM8: Institutional Action Plan for Resilient Water Supply addressed to water utilities, water authorities and civil protection, respectively).

3. RESULTS AND DISCUSSION

3.1. SWOT analysis

The tables reporting the outcomes of the SWOT analyses in relation to both the 'national' and 'utility' level on droughts, floods and earthquakes are attached to this paper as Supplementary Material (SM1, SM2 and SM3 for drought, floods and earthquake-related risks, respectively). These tables summarize the common issues among ADRION countries, as identified by the WUs through the questionnaires fulfilled in the first phase of the SWOT analysis. An analysis performed crossing the three analysed hazards allowed us to identify some common issues related to natural hazards that according to the stakeholders need to be carefully addressed for the sound development and implementation of WSPs. Results are presented in Figure 3.

The SWOT analysis carried out at both national and utility levels on droughts, floods and earthquakes allowed us to identify the main bottlenecks the WUs have to face for a suitable and robust development and implementation of WSPs.

In the following, we point out the main elements arising from the performed SWOT analysis concerning the first five modules (described later) for planning a WSP as illustrated in the WSP Manual (WHO 2009). Moreover, some possible solutions suggested by the stakeholders (thus feasible, according to their experience) are presented.

STRENGTHS

Relatively good status of water resources

High-level technical skills and scientific manpower in large WUs, also based on collaboration with research institutions

Well-developed monitoring networks at national level, also in real-time

Experience and knowledge related to previous events

Good civil protection organisation

Notifications of hill-functioning by users

WEAKNESSES

Uneven spatial and temporal distribution of water availability

Hydrologically poor areas with high water demand as well as temporal and spatial imbalances of water demand

Conflict of uses (drinking water, irrigation, energy production, recreative uses, ecosystem services)

Coordination difficulties stemming from fragmentation and overlapping of responsibilities in water management (both in emergency and ordinary conditions)

General lack of comprehensive models simulating impacts over time (early warning systems and risk analysis procedures)

Lack of skilled staff in small WUs

Lack of interconnections among different WSSs

Lack of a national registry for hazard events and impacts

Infrastructural ageing and old design criteria

Limitedness of resources (economic, technical, financial) particularly in small WUs

OPPORTUNITIES

Access to EU funds; access to national and regional funds

Availability of tools and technologies to support decision-making in ordinary emergency management

Increasing availability of smart monitoring and control systems

Fostering knowledge exchanges among neighbour WUs and transboundary systems to support interconnections

Rehabilitation of aged infrastructure, where reduction of water losses goes along with the improved resilience

Identification of alternative water resources (desalinated or treated waters, not exploited or partially exploited aquifers, etc)

Assessment of possible interconnections with neighbour WSSs

THREATS

Unsuitable land management/spatial planning

Climate changes (increasing temperature, heavy short-term rainfalls, decreasing availability of water resources, increasing water needs etc.)

Rapid loss of social memory of the dangers of hazards

Conflict of uses (drinking water, irrigation, energy production, recreative uses, ecosystem services), possibly exacerbated by water scarcity

High seismicity in several areas of Southern Europe

Figure 3 | Summary of common issues among flood, drought and earthquakes, identified with the SWOT analysis.

3.1.1. Module 1 – preliminary actions, including assembling the WSP team

Bottleneck: Many elements of weakness cited in the SWOT analysis refer to the lack of data and shared risk analysis procedures at a scale larger than the scale of the single WU. This need potentially affects all the modules of the WHO guidelines for a sound WSP development, from natural hazard monitoring to the estimate of impacts and related risks. It is worth stressing that the SWOT analysis clearly pointed out the lack of specific expertise and technical resources in small WUs. Not infrequently, in small WUs, there is a lack of a WSS model, and/or modern/automated management, sometimes even a scarcity of basic system data.

Suggested solution: From the start, it is necessary to set up a multidisciplinary team involving: (1) data providers (environmental, meteo-climatic, seismic, etc.), (2) institutions entrusted for planning, management or emergency, (3) external experts and (4) stakeholders that address the concurrent water uses. It is suggested to constitute different teams in relation to specific hazards. Moreover, setting up consortia of several WUs acting on neighbour territories can foster the individuation of common strategies to increase drinking water safety, as well as reduce costs for experts' teams.

3.1.2. Module 2 – describe the water supply system

Bottleneck: The performed SWOT analysis highlighted the necessity to first characterize each WSS by structuring the analysis in a shared scheme, which is able to represent all the components of the WSP, crossing each component with possible hazardous events and multihazard impacts. It is advisable to implement different approaches for the analysis in relation to the size of the WU, as listed in the following.

- Small WUs need guided and standardized procedures for the first screening of their own systems.
- Medium and large WUs very often have to deal with complex supply systems for which it is necessary to develop different WSPs related to different 'subsystems'. The 'subsystems' should account for the chain of impact of hazardous events considering their propagation. This significantly multiplies the number of plans to develop, overloading the necessary work (to both the WUs and the institutions entrusted with the approval steps).

Suggested solution: The need for small WUs of guided and standardized procedures for a first screening of their own systems has been addressed by developing the tool described in section 2.2 whose results are summarized in section 3.2. The issue of the high number of plans to be developed by medium and large WUs was not faced in this paper.

3.1.3. Module 3 – identify the hazards and assess the risks

The performed SWOT analysis pointed out several elements of weaknesses related to the identification of the hazards and assessment of the risks.

- *Probability of occurrence estimations*

Bottleneck: With reference to drought and flood hazards, the assessment of the 'probability occurrence' (estimation of return periods) usually needs a long time series of data to perform statistical analyses. The lack of long time series is one of the main problems to be faced. This is due either to an actual lack of data or to the fragmentation of data providers and/or accessibility to the existing databases. Moreover, some of the information necessary for risk analysis is not simply based on direct observations but relies on models able to simulate physical processes or establish statistically significant links. Modelling approaches are not usually adopted, especially by the small and medium WUs.

Suggested solution: Concerning the lack of long time series, it is suggested to foster the accessibility and interoperability of different databases to strongly increase the number of data available to perform sound risk analysis. Concerning the modelling activities, as for module 1, it is suggested to set up consortia of several WUs, when the necessary expertise is internally lacking.

- *Impacts data collection*

Bottleneck: Considering natural hazards one of the main bottlenecks for a robust risk analysis is to collect data on the impacts of such events good and numerous enough to perform a robust statistical analysis able to link hazardous events and impacts, mostly in cases of multihazard and non-linear impacts. The most important limitation is due to the lack of a shared 'catalogue of impacts' enabling us to feed off a shared database and thus increasing the statistical population of the impacts. Such kind of need is particularly important when dealing with WSSs, due to several reasons: (a) the entire chain from water resources to users is prone to several hazards, in some cases overlapping, such as natural hazards, chemical, and biological; (b) monitoring of hazardous events is entrusted to different actors (WUs, monitoring agencies, regulatory agencies, public institutions, civil protection); (c) conversely, monitoring of impacts is usually entrusted to the only water manager, preventing an effective sharing of impact data; (d) WSSs are sometimes shared by different countries, forcing an effective sharing of data and procedures.

Suggested solution: It is strongly suggested to set up a national, structured 'catalogue of impacts' of hazardous events on WSSs that includes: components of the system under study; a catalogue of possible hazardous events; a catalogue of possible impacts and relationships with triggering hazardous events; catalogue of possible mitigation measures. Catalogues should be shared and acknowledged by all the actors involved in water management with the aim of significantly increasing the statistical basis necessary to soundly estimate the probability of occurrence of the impacts. Currently, a structured 'catalogue of impacts' (at least in the ADRION area considered in this work) is missing both at national and transnational scales.

- *Climate change*

Bottleneck: Climate change is strongly threatening the resilience of water supply systems (mainly those that rely on a single water source) due to the current and future increase of extreme events.

Suggested solution: It is advisable to share among WUs belonging to homogeneous climate areas analyses of the current modification of the precipitation and temperature regime, as well as to assess the future P and T regimes and related impacts on the availability of water resources taking advantage of the global and regional climatic models. From the perspective of a multihazard approach, these climate, hydrological and hydrogeological analyses appear to be mandatory also when considering hazards not directly related to climate change (such as earthquakes): the overall availability of water resources strongly impacts the overall risk in case of superposition of different effects along the 'chain of impacts' that can lead to water shortages (whatever the trigger).

- *Future water needs and consumption*

Bottleneck: The development of an effective WSP calls for a robust estimate not only of the current and future water availability but also of the current and future water needs and consumption, especially in cases of concurrent uses. In the studied areas, these data and estimates are often provided (when existing) by different institutions and, until now, there is not a centralized database.

Suggested solution: It is strongly suggested to foster an effective multilevel water governance to set up centralized 'observatories' at the scale of the largest watershed basins involving not only drinkable water managers but also water managers for other uses (irrigation, energy production, etc.).

3.1.4. Module 4 – determine and validate control measures, reassess and prioritize the risks

Bottleneck: Traditionally, information on the impacts of natural hazards such as drought, flood or earthquake on water resources during past events still relies on ground data. With respect to flood, for example, the extension of the flooded areas was derived in the past by fragmentary data sources (e.g., pictures, videos, direct testimonies, indications derived from videos recorded during helicopter flights, etc.), therefore uncertainty can affect the identified area.

Possible solution: Nowadays, the use of high-resolution satellite data can represent a significant improvement (Demirel *et al.* 2018; Alfieri *et al.* 2022), especially when integrating with ground data through modelling approaches (big data analysis, digital twin approaches, etc.). It was recognized by several water utilities that such an approach can be very useful to reassess and prioritize the risks, but that usually overcomes the internal skills and competencies of the WUs, especially of the smallest ones.

3.1.5. Module 5 – develop, implement, and maintain an improvement/upgrade plan. Investment required for major system modification

Bottleneck: The actual status of the WSS infrastructures and their actual vulnerability to natural hazards is often missing. From the performed SWOT analysis, problems related to infrastructural ageing and old design criteria clearly emerge.

Possible solution: To support the identification of the investments required for major system modifications, it appears to be necessary to perform robust risk analyses based on the integration of different elements: (a) local estimation of the statistical characteristics of a specific hazard; (b) evaluation of the impacts on the single component of the WSS accounting for its specific vulnerability, also in relation to its age; (c) possible impact along the 'chain of impacts'. Such an analysis should support the identification of the investments required for major system modifications.

3.2. WASPP-DSS

Results from the implementation of the tool WASPP-DSS on the single water supply systems are out of the scope of this paper. However, a detailed survey performed during the testing phase performed over 12 pilot cases (Table 1) allowed us to identify some strengths:

- The tool is coherent with the WSP manuals provided by the World Health Organization (WHO 2009, 2023).
- It provides a comprehensive list of possible hazardous events, which appears very useful to support the initial screening and rank the riskiest events.

- The structure of the tool, organized into 'components' and 'subcomponents', allows us to perform a comprehensive risk analysis from resource to tap, following the entire chain.
- Having a shared scheme of analysis may boost comparison among different WSPs, promoting collaboration among WUs acting in close territories or, in some cases, having interconnections.
- The final report and most of all the possibility to visualize the results 'per component', 'per hazard' or 'per level of risk' suitably supports the screening phase.

On the other side, some important limitations have been highlighted by the WUs, such as:

- Drinking water chain can be quite complex; the user should evaluate, in the same WSP, multiple drinking water sources with different treatments, etc. and such a complexity cannot be handled by the WASPP-DSS.
- To perform a robust estimate of the risk matrices one should take into account also two more elements (not accounted in the current version of the tool): (a) the multihazard dimension, when effects of different hazards overlap; and (b) the propagation of impacts through the whole chain from resource(s) to tap.
- The tool does not allow for taking into consideration the spatial dimension of water infrastructures, implying that spatial relations and related impacts among components (as well as the direction of such impacts) are not explicitly considered.
- The assessment of the occurrence probability of a given hazardous event is usually quite difficult and several WUs (small and medium ones) do not have data time series long enough to perform such an assessment. This is a typical situation where the support of monitoring agencies specifically entrusted to collect data necessary to assess the probability of occurrence, vulnerability and related risks is mandatory.
- The assessment of the vulnerability of the single components in relation to a given hazard (or superposition of hazards) and the related probability of occurrence is challenging at the level of WUs; organizing and continuously feeding a national and transnational registry of impacts of natural hazardous events on WSSs appears to be mandatory.

The limitations highlighted by the WUs in the WASPP-DSS testing phases allowed us to better address some of the specific objectives proposed in the strategic document described in section 3.4 and entirely reported in the Supplementary Materials (SM6, SM7 and SM8).

3.3. Tabletop exercises

Results obtained from testing the TTXs guidelines (Table 2 and SM4) on performing TTXs showed important considerations. Regarding the actors involved in the exercise, it was noted that they should focus mainly on:

- Drafting (or improving/updating an existing) written contingency plan.
- Compilation of a directory of the persons in charge of the involved services including their contact details.
- Clarification of roles and responsibilities.
- Creation of a core of selected staff for emergencies.
- Training and education for the staff that will make the initial assessment of the situation in order to report the correct information without overestimating or underestimating the consequences of the emergency.
- Coordination/cooperation with third parties (agencies, services).
- Procedures for public communication in emergencies.

The results of testing the guidelines were also useful to give specific hints for the future development of standardized TTXs:

- The set-up of a regional technical table is identified as the key measure for the effective, synergistic, and timely connection and coordination of all the bodies responsible for the management of water resources, water quality control, water regulation and civil protection activities.
- It is strongly suggested to perform a preparation activity to TTX in order to achieve, albeit in a provisional way, the sharing of tools, languages and procedures, including innovative ones (for example, the definition of thresholds for the activation of the operational phases).
- The continuous flow of information and updating of the event and impact scenarios and the link between the procedures are good practices for effective mitigation measures.
- It is necessary to better connect civil protection and WUs and give feedback regarding important matters in case of hazardous events.
- In the case of the drinking water supply, a database on the availability of spare parts should be set up.

- If the entire cross-border management system has been reduced to the level of utility companies, small utilities cannot handle this task and responsibility.

To deal effectively with emergency events, it is necessary for civil protection operators to be aware of the tasks both in the phase that precedes a possible emergency and during the emergency itself. For this purpose, it is fundamental to implement adequate training programmes for the operators to be tested during exercise activities.

The inter-institutional relationship among WUs, civil protection systems and water agencies is highly complex and dynamically evolving and it should involve many other public and private institutions, especially in a very fragmented institutional framework. Although water management in all countries is based on EU policies and directives, the application of the guidelines has to be flexible due to differences in size (large, medium, small), spatial scale (regional, local), source (groundwater, surface water or mix) of the DWSs and institutional framework.

Based on the results of the TTXs, it proposed an action plan (SM5) for the development of TTXs for improved WSP reliability. The AP, primarily addressed to WUs, is based on an integrated approach ensuring the logical sequence of actions and link to the strategic vision and includes all necessary elements to ensure the achievement of the strategic goals. The action plan is developed along three priority axes:

1. Improvement of water safety planning and monitoring procedures oriented to preparedness and emergency responses.
2. Increase of governance structures and interagency cooperation effectiveness, also in a transnational context.
3. Improvement of the necessary measures facilitating the effective function of the water safety planning mechanism.

The results strongly suggested that TTXs are excellent tools useful for fine-tuning and better defining operational plans and procedures, as well as making the various parties involved in the management of the event interact with each other.

3.4. REWAS-ADRION strategic document

The REWAS-ADRION strategy is developed along five priority axes and includes seven targets (Figure 4). It was then developed in specific action plans addressed to water utilities, civil protection and water agencies. Specific and practical objectives, related to the priority axes and targets of the REWAS-ADRION strategic documents, have been indicated in the action plans. For each objective, activities, instruments, stakeholders to be involved and possible constraints are proposed. The list of the specific objectives is reported in Table 4.

Figure 4 | Priority axes and targets of the proposed REWAS-ADRION strategic document.

Table 4 | Summary of the specific practical objectives reported in the Action Plans for Water Utilities, Civil Protection and Water Agencies (SM6, SM7 and SM8)

	Priority axis	Specific objective
Water utility	1	Elimination of the gap of information and the bottlenecks at staff members' level (emergency response mechanism)
	1	Reduction of difficulties in the development and constant implementation of the water safety plan (inter sectoral cooperation, integration of the water safety plan in water utility's operation)
	1	Recognition of existent procedures and mutual knowledge of the roles and competences of each organization
	2	Enhancement of interagency operation among the responders in the area of water utility's responsibility (emergency response mechanism)
	3	Enhancement of the feasibility of the water safety plan (evaluation/review aspects)
	3	Operational capacity building of water service providers & stakeholders, to support the effective implementation of water safety mechanism procedures
	5	Strengthening public awareness on water safety issues
	5	Improvement of interagency communication and interoperability capacity within water safety mechanism
Water agency	1	Assessing drought conditions, reducing drought risk in advance and developing response options that minimize economic stress, environmental losses and social hardships during droughts
	2	Enhancement of interagency operation among the responders in the area of water utility's responsibility (emergency response mechanism)
	3	Increase organizational preparedness under crisis situations
	4	Identification of institutional actors and stakeholders to overcome the mismatch between hydrological and administrative boundaries
	4	Increase the availability of the information on water supply systems for the purpose of decision-making process during the emergencies
Civil protection	1	Recognition of existent procedures and mutual knowledge of the roles and competences of each organization
	2	Enhancement of inter-institutional cooperation in the field of water resources management
	4	Water System Information improvement

It is worth emphasizing that the REWAS-ADRION strategic document is not intended as a 'comprehensive' document, covering all the topics to be tackled in developing and implementing WSPs. It is rather a document that points out the main issues related to natural hazard risk analysis in the framework of WSP and suggests some lines of interventions mainly aimed at fostering interagency cooperation in the field of resilient water supply. As a matter of fact, all the activities performed with the stakeholders and here presented are indicated as fundamental requirements to tackle natural hazards in the context of WSPs the inter-institutional cooperation both at planning and at operational level.

4. CONCLUSIONS

Despite the large number of methods adopted and the findings of this study, it is possible to point out some main practical goals to be addressed to enhance the water supply system's resilience to multi-natural hazardous events in the framework of WSPs:

- to guarantee the interoperability among different databases, possibly structured on a GIS basis;
- to develop and implement comprehensive models simulating impacts over time (early warning systems and risk analysis procedures) and shared among all the possible involved stakeholders (mainly in case of co-exploitation);
- to organize and continuously feed a national and transnational registry of impacts of natural hazardous events on WSSs;
- to carry on detailed and comprehensive risk analyses about climate change impacts on DWSSs adopting a multihazard approach; to this end, the support of the scientific community is highly recommended.

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AUTHOR CONTRIBUTIONS

E.R., P.B., B.C.C., and V.K. conceptualized the whole article, developed the methodology, and arranged the software; E.R., J.A., V.K., D.D., B.M., P.B., I.B., E.C., B.C.C., A.D., D.K., A.P., A.P. J.L.R., M.S., and S.T. rendered support in data curation, investigated the work, and validated the data; E.R. and J.A. wrote the original draft and supervised the work; E.R., J.A., V.K., D.D., and B.M. wrote the review and edited it; E.R. and J.A. rendered support in project coordination.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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