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Climate-related risk assessment in water safety plans: the case study of Acque Bresciane (Italy)

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ABSTRACT

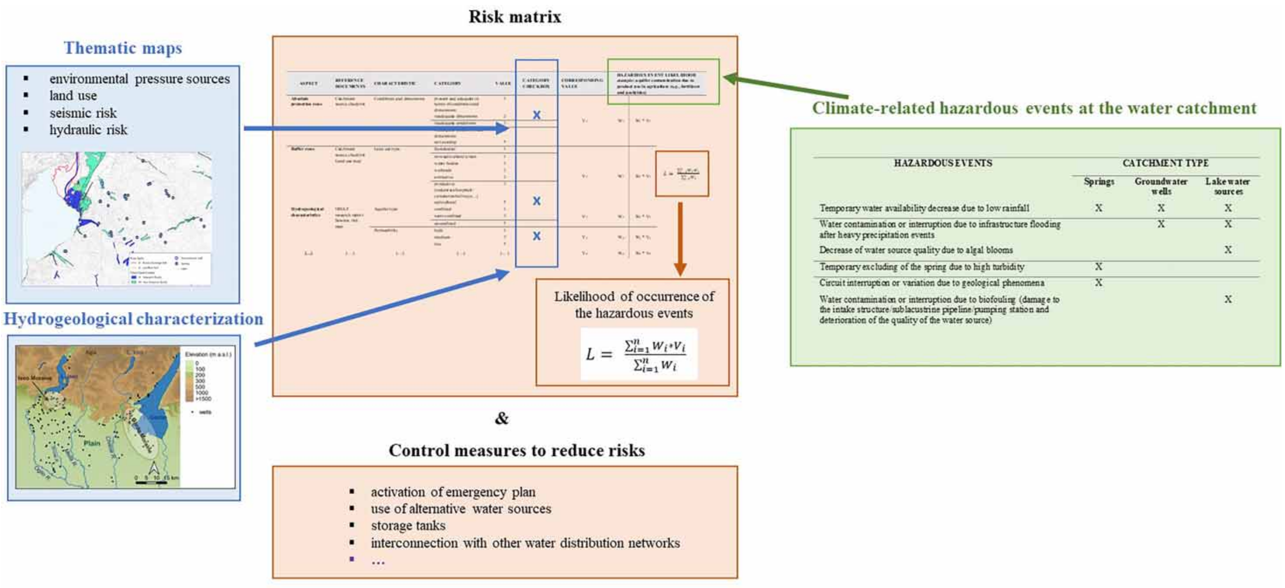
Acque Bresciane is a public company that manages the integrated water cycle for more than 580,000 inhabitants in the Province of Brescia, in the north of Italy, providing drinking water, waste water treatment, and sewer systems. Drinking water systems are supplied with different types of groundwater, springs, and surface water sources (from lakes and rivers) whose availability and quality can be affected by climate change events. A multidisciplinary team, in collaboration with the University of Milano Bicocca, developed a specific Water Safety Plan (WSP) risk matrix focusing on the evaluation of climate-related hazardous events and calculation of their likelihood of occurrence, also using thematic maps. Moreover, to reduce the residual risks, in the risk matrix, possible control measures are suggested, such as the activation of an emergency plan, the use of other water sources, storage tanks, and interconnection with other water distribution networks. This work shows a simple and effective tool that can be applied by drinking water utilities to evaluate climate-related catchment risks, using a WSP risk matrix, thematic maps, and possible control measures to reduce risks in terms of water quality and availability and to respond with resilience to changes.

Key words: catchment, climate change, drinking water quality, risk assessment, risk matrix, water safety plan

HIGHLIGHTS

- A risk assessment tool was developed to evaluate climate-related hazardous events in WSPs.
- Three catchment matrices were developed for wells, springs, and surface waters.
- Control measures were suggested to reduce the residual risks of climate change-related events.
- The matrices can be replicated for all drinking water supply systems.
- This simple and effective tool can be applied by all drinking water utilities.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Water Safety Plans (WSP), increasingly applied by water utilities around the world and mandatory in Italy (Italian Legislative Decree 18/2023), can be considered as the best approach to ensure a safe drinking water management, which must consider drinking water quality, acceptability, and quantity in the context of public health protection. Water safety planning considers risk assessment of the entire water supply chain, from the catchment to the user, through a 'multiple-barrier' approach, ensuring that if one barrier (or control measure) fails, other barriers should help guarantee water safety to the user (WHO 2023).

Long-term planning for an adequate and safe supply of drinking water should be set in the context of growing external uncertainties arising from changes in the climate and environment. In fact, future projections provided by a large number of scenarios and modelled pathways state that global warming will continue to increase in the next 20 years (based on 2021–2040 projections), affecting all components of major climate systems and leading every world region to experience multiple and co-occurring changes (IPCC 2023). The WSP process offers a systematic framework to manage these risks by considering the implications of climate variability and change (WHO 2017a).

Examples of climate change-related events which can affect drinking water supply systems are increased surface runoff due to heavy rainfall that contaminates water sources, increased concentration of pollutants in source waters due to extreme drought periods, and favourable growth conditions for pathogens due to increased water temperatures (Whitehead *et al.* 2009; Javadinejad *et al.* 2019; Ranasinghe *et al.* 2021). These extreme weather events may have quantitative impacts on water availability, by damaging infrastructure and distribution systems, and may also affect water quality (Delpha *et al.* 2009; Wang *et al.* 2022).

Water suppliers are already dealing with climate-related events such as heavy rainfall or droughts during their normal operation, but not all of them have developed a systematic tool for risk assessment in WSPs. In fact, according to WHO (2017b), climate change evaluation has been integrated in WSPs in diverse regions of the world, making water suppliers resilient to the anticipated effects of climate change, but there is only limited information published in English on how to integrate climate change aspects into WSPs (Rickert *et al.* 2019). Therefore, there is an urgent need to develop simple and easy to use tools for the evaluation of climate change-related events in water safety planning, to support access to safely managed and resilient drinking water supplies for all users, despite future uncertainties (WHO 2023). Knowledge about the expected changes in climate has to be built up and the vulnerability of the system should be examined (Staben *et al.* 2015), considering that the relationship between climate change and drinking water safety is complex and various kinds of factors play an important role, such as the water treatment technology, the distribution system, public awareness, the local economic development level, the frequency of extreme events, and the accuracy of weather forecasts (Ma *et al.* 2022).

Building climate resilience into existing risk management approaches such as WSPs appears to offer one of the most cost-effective approaches to managing climate risks, even if in some cases investments in new infrastructure or catchment management will be required (Howard *et al.* 2016). In particular, water utilities should evaluate the catchment vulnerability to climate-related events in the framework of WSPs, also by using data available from national or regional geoportals, through an active collaboration with the environmental protection agencies. This data should help water utilities in developing standard risk assessment tools, such as the catchment risk matrix, to increase the efficiency of WSPs.

This work shows the specific catchment risk assessment matrix developed by the Italian water utility Acque Bresciane in collaboration with the University of Milano Bicocca. Acque Bresciane is a public company that manages the integrated water cycle for more than 580,000 inhabitants in the Province of Brescia, in the north of Italy, providing drinking water, waste water treatment, and sewer systems. The territory stretches from the mountains (pre-Alps) in the north to a wide plain in the middle and south, and it is enclosed between two main lakes, Iseo and Garda (Figure 1). Considering the variety of landscapes, drinking water systems are supplied with different types of groundwater, springs, and surface water sources (from lakes and rivers). Drinking water comes from 207 groundwater wells mainly located in the plain, 233 springs located in the northern Piedmont and mountain area, 7 lake water sources (6 in Garda Lake and 1 in Iseo Lake), and 11 stream water sources in the mountain area.

To ensure the health and safety of water for human consumption, Acque Bresciane in 2017 started a project with the aim of developing risk assessment and management of all its drinking water supply systems, through WSPs, following the World Health Organization (WHO) and the Italian National Guidelines on WSPs (WHO 2009; Lucentini *et al.* 2014). Moreover, the subsequent updates of the guidelines were considered for recent developed WSPs (Istituto Superiore di Sanità 2022; WHO 2023), as well as the European Directive 2020/2184 (Directive EU 2020/2184) and the related Italian Legislative Decree 18/2023, concerning the quality of water intended for human consumption (Italian Legislative Decree 18/2023).

With the development of the WSPs, all possible hazardous events and related hazards that may impact the quality and quantity of the water resource were analyzed. Moreover, effective control measures were defined to mitigate risks, reducing emergency situations. Three specific matrices were created to analyse the likelihood of occurrence of hazardous events that could affect the catchment sources managed by Acque Bresciane, in particular groundwater, springs, and surface waters.

Europe, from the 1980s, has warmed more than twice the global average, figuring as the fastest-warming region (WMO 2023) and facing an increase of extreme climatic events, like pluvial flood, aridity, and hydrological drought (Ranasinghe *et al.* 2021). Within this overall framework, focusing on Northern Italy, research and models shows that in this area drought episodes (since 2001) have become more frequent and more lasting and extreme rainfall events have increased in terms of duration and precipitation height (Pieri *et al.* 2016; Caloiero *et al.* 2021). It was therefore considered important to place a specific focus on the impact of climate change on the aforementioned water sources, to plan their management in the medium-long term. The matrices were developed and discussed by the WSP team and were compiled by using thematic maps. A specific study was carried out to classify water bodies in relation to water availability and vulnerability with respect to possible scenarios of climate change, especially by identifying the mitigation aspects that can be adopted to respond with resilience to changes. This study regarding the hydrochemical characterization of the water catchment sources is described in a previous work (Zanotti *et al.* 2022), aimed at identifying the main natural and anthropogenic processes that influence the characteristics of the water sources. This work is useful for the vulnerability assessment of the catchments, since it describes the aspects of inherent vulnerability to natural and anthropogenic phenomena.

2. METHODS

2.1. Acque Bresciane WSP team

Acque Bresciane WSPs are developed by a multidisciplinary team that includes representatives from several institutions and organizations, each giving a specific contribution to the plan development, according to the area of interest.

In more detail, Acque Bresciane WSP team is composed as follows:

- *Acque Bresciane* (https://www.acquebresciane.it/): Water utility that coordinates the WSP team and develops WSPs. An internal team leader is head of the project and 30 coworkers collaborate and participate in periodic meetings with the aim to share and discuss WSP results. Within this internal team, a specific Core Team is involved in WSP development, including site inspections, data collection and elaboration, risk matrix development, and control measure definition.

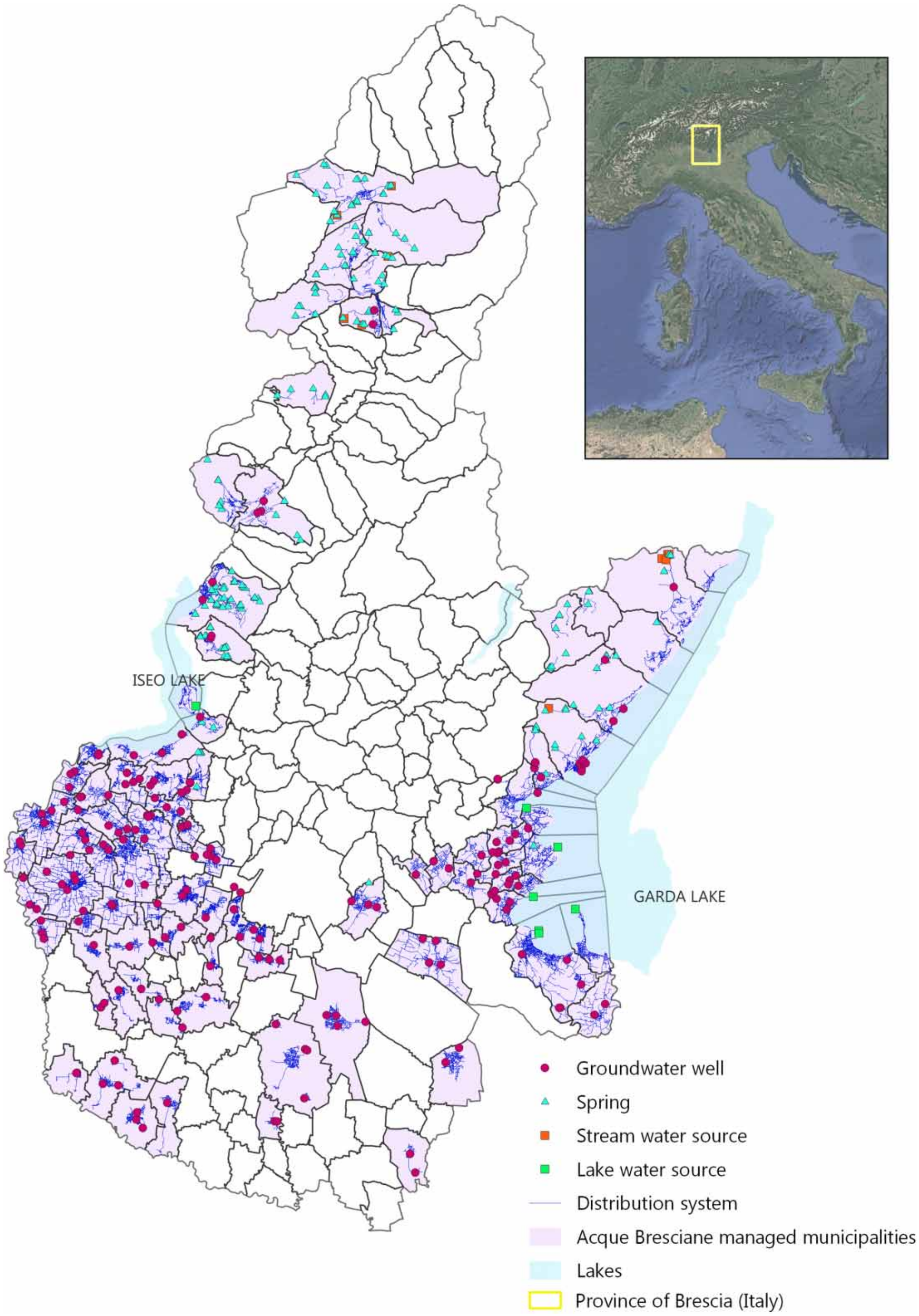


Figure 1 | Acque Bresciane drinking water supply systems.

This team consists of specialists from operational and technical areas, each contributing by providing data, sharing knowledge, and suggesting control measures to reduce risks, based on their own skills and experience. For instance, some of the Core Team members are as follows: drinking water supply system manager, water network manager, electrical area manager, maintenance area manager, and waste management coordinator.

- When a WSP is completed, a first meeting is organized with all the Core Team members, to share and discuss all the risks and proposed control measures. Then the WSP is presented and discussed in one or more internal team meetings, involving members of the following areas:

- operational area;
- technical area;
- laboratory;
- quality area;
- communication and public relations office;
- sustainability office.

- *Health Protection Agency of Brescia* (Agenzia di Tutela della Salute – ATS – Brescia; https://www.ats-brescia.it/): Organization responsible for implementation of the regional social and health program, provision of health services and health monitoring, and prevention in public and work environments. As a WSP team member, ATS provides drinking water quality analysis of sampling points in the distribution system.
- *Regional Environmental Protection Agency* (Agenzia Regionale per la Protezione dell'Ambiente – ARPA Lombardia; https://www.arpalombardia.it/): Organization that works for the environment prevention and protection, supporting regional and local institutions in a wide range of activities, e.g., air and noise pollution control, surface water and groundwater protection, soil contamination investigations, and remediation processes. ARPA contributes to WSP development by providing analysis of raw water sources from wells and lakes, hydrogeological information, and georeferencing of environmental pressure sources, such as landfills and contaminated sites, that could affect water quality.
- *Local Water Authority of Brescia* (Ufficio d'Ambito di Brescia; https://www.aato.brescia.it/): Administrative governing authority that gathers local governments, provinces, and municipalities, which carries out the functions of planning, scheduling, supervising, and controlling the integrated water cycle. This office supervises the activities proposed in the WSP and monitors the water utility investment plan, to ensure that the integrity of the water supply system, facilities, and other assets is safeguarded.
- *University of Milano Bicocca*: The Department of Earth and Environmental Sciences (DISAT; https://www.disat.unimib.it/it/il-dipartimento) developed an important research project to support WSP risk assessment through the identification of possible hydrogeochemical hazardous events (a cost-effective method for assessing groundwater well vulnerability to anthropogenic and natural pollution in the framework of water safety plans) (Zanotti *et al.* 2022). The approach combines hydrogeological, hydrochemical, and hydrodynamical characterization of the water sources managed by Acque Bresciane and used for human consumption. In particular, the DISAT research team collaborated in the catchment risk matrix development;
- *Cogeme Foundation* (https://fondazione.cogeme.net/): This is a non-profit organization founded with social solidarity purposes in support of the territory, in particular the Franciacorta region and the western plain of the Province of Brescia, in synergy with local communities, associations, businesses, and institutions. It develops numerous environmental, social, educational, and cultural projects according to the principles of sustainable development and circular economy. As a WSP team member, it supports the communication activities, such as public conferences to present WSPs to the population, in collaboration with the municipalities, and information campaigns for customers and school students to promote drinking of tap water;
- **Consultants**: Advise on technical aspects concerning drinking water treatments;
- **Municipality**: Provision of public data useful for risk assessment and collaboration with the water utility to the development of a proper and effective information campaign. The municipalities involved in each WSP team depend on the administrative areas supplied by the specific drinking water system. Therefore, a WSP team can involve one or more municipal authorities if the studied water supply network supplies one or more municipalities.

2.2. Catchment risk matrix

Considering risk assessment at the water catchment, the WSP team in collaboration with the University of Milano Bicocca elaborated a specific risk matrix to evaluate vulnerability to anthropogenic and natural pollution, including both hydrogeological and hydrochemical aspects that can affect climate-related hazardous events.

The risk matrix was elaborated following the principles of the WHO WSP manual (WHO 2009) and the WSP Italian guidelines issued by the National Institute of Health (Istituto Superiore di Sanità – ISS) (Lucentini *et al.* 2014) and by using the spreadsheet software Microsoft Excel.

According to the WHO and ISS guidelines, the risk matrix was developed to calculate the risk as the product of three parameters: likelihood (of occurrence of each hazardous event), severity (of the consequences), and detectability (of the hazards). Each parameter was calculated in a specific risk matrix; thus, three main matrices were developed. Considering the likelihood risk matrix, a specific submatrix was developed for each part of the drinking water supply system, for example, catchment, treatment plant, and distribution network. Considering the catchment, specific likelihood matrices were developed for each kind of water source: groundwater, surface water, and spring. The following paragraphs describe in detail the structure of each catchment likelihood risk matrix.

The list of catchment hazardous events and hydrogeological aspects in the matrices were defined in collaboration with the University of Milano Bicocca, as mentioned earlier.

2.2.1. Structure of the analysis sheets for likelihood calculation

A catchment risk matrix was created for each type of water source managed by Acque Bresciane in the province of Brescia. Three different analysis sheets were implemented, one for each of the three water source types: groundwater (wells), springs, and lake water sources.

These matrices allowed the calculation of the likelihood by combining two parameters:

(1) Catchment characteristics: aspects that affect the likelihood of occurrence of a certain hazardous event. The following categories of aspects were considered:
  a. safety and characteristics of the wellhead protection zone;
  b. infrastructural characteristics of the water assets;
  c. environmental characteristics (hydrogeological or ecological)

(2) Hazardous events: incidents or situations that can lead to the presence of a hazard (i.e., biological, chemical, physical, radiological) in drinking water.

The three matrices differ partially in content, but the general structure is the same, and it is organized as follows (Table 1):

– column 1, named 'aspect,' lists the categories of aspects to be analysed, e.g., abstraction safeguard zone characteristics;

Table 1 | Extract of the risk matrix structure (V = value, W = weight, L = likelihood)

Aspect	Reference documents	Characteristic	Category	Value	Category checkbox	Corresponding value	Hazardous event likelihood *example:* aquifer contamination due to product use in agriculture (e.g., fertilizers and pesticides) Weight	Value-by-weight	Average likelihood
Absolute protection zone	Catchment source checklist	Conditions and dimensions	Present and adequate in terms of conditions and dimensions	1		V_1	W_1	$W_1 * V_1$	$L = \frac{\sum_{i=1}^{n} W_i * V_i}{\sum_{i=1}^{n} W_i}$
			Inadequate dimensions	2					
			Inadequate conditions	3					
			Inadequate conditions and dimensions	4					
			Not existing	5					
Buffer zone	Catchment source checklist Land use map	Land use type	Residential	1		V_2	W_2	$W_2 * V_2$	
			non-agricultural green	1					
			water bodies	1					
			wetlands	2					
			extractive	2					
			productive (industries/ hospitals/cemeteries/ railways…)	3					
			agricultural	5					
Hydrogeological characteristics	DISAT research report	Aquifer type	confined	1		V_3	W_3	$W_3 * V_3$	
			semi-confined	3					
			unconfined	5					
	Seismic risk map	Permeability	High	1		V_4	W_4	$W_4 * V_4$	
			Medium	3					
			Low	5					
[…]	[…]	[…]	[…]	[…]		V_n	W_n	$W_n * V_n$	

- column 2, named 'reference documents,' reports the name of the WSP documents where information about the aspects can be found;
- column 3, named 'characteristic,' lists the characteristics of the categories of aspects, e.g., the types of access to the wellhead protection zone, the presence or absence of waterproofing in the area, and so on;
- column 4, named 'category,' provides a classification for each characteristic, e.g., with regard to the type of access to the abstraction safeguard zone, it can be classified as 'adequately protected' or 'inadequately protected';
- column 5, named 'value,' reports a value from 1 to 5 that corresponds to each class of column 4, considering its influence (1 low, 5 high) on the occurrence of each hazardous event (e.g., adequately protected 1, inadequately protected 5). The value assignment was shared and defined by the WSP team.

The following five columns (6–10) of the risk matrix can be replicated for each catchment (well, spring, or surface water intake) and were structured as follows:

- column 6, named 'category checkbox,' must be compiled by the user filling an 'x' symbol beside the selected class of column 4. For example, if the absolute protection zone shows inadequate dimensions, an 'x' should be put in this column at the corresponding line 'inadequate dimensions' of column 4;
- column 7, named 'corresponding value,' automatically calculates and reports the corresponding value (from 1 to 5) based on the choice made in column 6. For example, if the absolute protection zone shows inadequate dimensions, column 7 will show the corresponding value '2'.

The following columns were created for each hazardous event:

- column 8 'weight': reports a value from 0 to 10 defined for each characteristic of column 3, considering its influence (0, none; 1, low; 10, high) on the likelihood of occurrence of each hazardous event. For example, considering the hazardous event 'vandalism,' the 'type of access' has an important influence, so weight 10 is assigned, while considering the hazardous event 'low water availability,' the same 'type of access' has no impact, so weight 0 is defined;
- column 9 'value-by-weight': reports the product between the weight (column 8) and the value (column 7). If weight is 0, this column has a null value meaning that the characteristic does not influence the likelihood calculation, thus the occurrence of the event;
- column 10: 'average likelihood': weighted average obtained by dividing the sum of value-by-weight;
- (column 9) by the sum of weight (column 8).

Table 1 shows an extract of the risk matrix structure. The full spreadsheets are shown in the Supplementary Material section (Tables 1S, 2S, and 3S). The complete list of characteristics and events is described in Section 3.

2.2.2. Catchment characteristics

Each risk matrix considered a list of infrastructural, hydrogeological, and environmental characteristics, reported in columns 1 and 3. These aspects were assessed in the spreadsheets to establish the likelihood of occurrence of each hazardous event.

The following infrastructural characteristics were considered:

- presence of properly protected access (for springs and wells) or properly marked delimitation (for lake intakes);
- fulfilment of the minimum dimensions of the absolute protection zone (10 m radius from the water source) and adequate condition of the area (characteristic not assessed for surface intakes), i.e., absence of inappropriately stored materials in the wellhead area;
- presence of adequate waterproofing of the absolute protection area (characteristic not assessed for surface intakes);
- type of delimitation criteria adopted for the definition of the buffer zone, e.g., temporal or geometric criteria;
- land use type in the buffer zone, based on land use map and checklists filled in during site inspections: residential, non-agricultural green, forests, water bodies, wetlands, extractive, productive (e.g., industries, hospitals), and agricultural;
- environmental pressure sources in the buffer zone, e.g., presence of disused/private/leaking wells, discharges of various types, livestock farms, cemeteries, landfills, contaminated sites;
- presence of alternative water sources in the supply area;
- position of the wellhead in relation to ground level (above or below the ground level);
- adequacy of the lake water intake structure with regard to its position and configuration;

– presence of protective grid on the water intake structure and assessment of its maintenance condition;
– state of maintenance of the sub-lacustrine pipeline;
– presence of adequate protected access to the pumping station;
– location of the electrical panels and of the wellhead in the pumping station in relation to ground level;
– absence of hazardous materials inside the building of the well or pumping station;
– presence of waterproofing of the upper well grout and overall assessment of its condition;
– presence of waterproofing of the structure where the catchment source and/or pumping station is located (e.g., waterproof covering or systems that prevent rainwater infiltration);
– slope management for springs and lake water sources;
– presence of systems to prevent animals from entering the premises attached to the intake structure (e.g., presence of insect grids on the openings);
– overall assessment of the state of maintenance of the infrastructure (e.g., deteriorated structural parts, doors to be replaced, hydraulic equipment to be renewed, and so on);
– presence of high hydraulic risk in the water catchment area;
– age of the pumps used in the structure (more or less than 8 years old);
– high seismic risk (according to Lombardy Region zoning) or risk of landslide events for wells and springs.

The following hydrogeological and environmental characteristics were considered with regard to the three types of catchment sources:

Wells:

– Aquifer type: Confined, semi-confined, or unconfined; this characteristic affects the vulnerability to anthropogenic surface contamination or natural origin contamination due to geology (i.e., contamination by reduced species, such as Mn, Fe, As, NH_4).
– Residence time of the captured aquifer: Average time elapsed between the infiltration of water into the subsoil and its extraction, which is a function of the water flow speed and the length of the circuit of the water in the subsoil. This characteristic has a weight in relation to contamination events of the aquifer due to both anthropic and natural origin. A 'short,' 'medium,' or 'long' time can be assigned, with a value scale that increases with the residence time in case of natural contamination by reduced species, and decreases in case of anthropic contamination.
– Aquifer depth (to be evaluated only for unconfined or semi-confined aquifers): Distance in metres between the ground level and the groundwater table, i.e., thickness of unsaturated soil, in order to assess the vulnerability of the well to groundwater contamination due to anthropogenic pressure sources. The risk matrix reports whether the aquifer underlies the ground level for more than 40 m, less than 20 m, or between 40 and 20 m.
– Average permeability of unsaturated soil (for unconfined aquifer) or of soil between the first filter and ground level (for semi-confined aquifer): This parameter can influence the occurrence of possible groundwater contamination due to environmental pressure sources and agriculture. Permeability was qualitatively parameterized according to the presence or absence of fine textures (clays and silts) in the well stratigraphy with three values: 'high' in the case of absence of significant layers of pure clay, 'low' in the case of presence of significant clay thicknesses, even on several levels, or 'medium' in the case of intermediate conditions.
– Groundwater circulation in naturally sulphate-releasing layers: The presence of sulphate and/or sulphide minerals in the solid aquifer matrix and their dissolution in groundwater was evaluated, resulting in high sulphates concentrations and potential contamination of the aquifer from natural sources; the presence or absence of sulphate-rich matrices is indicated in the spreadsheet with 'yes' or 'no.'
– Natural redox conditions: This parameter influences the vulnerability of the aquifer to natural contamination due to geology (contamination by reduced species). Four possible scenarios were identified: oxidizing conditions, initial reducing conditions (denitrification), mixed initial oxidizing/reducing and advanced reducing conditions, advanced reducing conditions (Mn/Fe reduction onwards).

Lake water sources:

– Trophic level of the lake: Oligotrophic lake, mesotrophic lake, or eutrophic lake. The water body is classified according to the availability of nutrients that support plant production (mainly nitrogen and phosphorus).

– Position (on the vertical) of the intake with respect to the euphotic zone: The position of the intake in relation to the layer of water to which 1% of solar radiation can reach. This is the depth up to which the development of photosynthetic species can be possible, called the euphotic zone. The lake catchment can be always below the euphotic zone, sporadically within the euphotic zone or always within the euphotic zone.
– Time elapsed since the most recent complete mixing of the lake: 1 year, from 2 to 7 years, or more than 7 years. This characteristic can influence the concentration of reduced chemical species on the surface.
– Percentage depth of the intake (intake depth/lake bottom depth × 100): Less than 30%, from 30 to 70%, and more than 70%. This parameter describes the proximity of the catchment to the lake bottom, to express the likelihood of catching deep and potentially anoxic water, and consequently, the vulnerability in terms of presence of reduced chemical species.
– Distance (m) of the intake from the shore: More than 200 m, from 200 to 50 m, or less than 50 m. This parameter can influence the vulnerability of the intake to environmental pressure sources such as discharges, livestock farms, cemeteries, landfills, or contaminated sites.

Springs:

– Spring/summer drought events in the last 6 years: 'Yes' or 'no,' considering the occurrence in the period before the WSP development.
– Autumn/winter drought events in the last 6 years: 'Yes' or 'no,' considering the occurrence in the period before the WSP development.
– Presence of sulphates of natural origin: 'yes' or 'no,' considering the presence of high concentrations of sulphates in the last 5 years.
– Vulnerability to surface anthropogenic impacts from site-specific studies: Not available, high, medium, or low. This parameter is defined considering the type of spring and how it interacts with the surface.
– Turbidity increase in the last 5 years: 'Yes' or 'no,' considering the occurrence in the period before the WSP development.

2.2.3. Thematic maps

The following thematic maps were created for each drinking water system to support the risk assessment by using the Open Source software QGIS:

- environmental pressure sources;
- land use;
- seismic risk;
- hydraulic risk.

The thematic map of the environmental pressure sources, using regional technical map as background (obtained from Lombardy Regional Geoportal; https://www.geoportale.regione.lombardia.it/), shows the following points:

- contaminated sites (source: ARPA Lombardia);
- disused/private/leaking wells, discharges of various types (source: ARPA Lombardia);
- cemeteries (source: ARPA Lombardia);
- landfills, ecological islands, waste storage facilities (source: ARPA Lombardia);
- sludge and waste treatment plants, including hazardous waste and composting plants (source: ARPA Lombardia);
- waste recovery plants (source: ARPA Lombardia);
- waste incinerators (source: ARPA Lombardia);
- georeferencing of farms surveyed by the Province of Brescia in 2010 (source: Provincial Territorial Coordination Plan (PTCP); https://sit.provincia.brescia.it/atlante/piano-territoriale-coordinamento-provinciale-ptcp-vigente);
- georeferencing of disused industrial areas surveyed by the Province of Brescia in 2010 (source: PTCP).

The thematic map of the land use shows the land use type for the territory that forms the object of this study, using as source 'Dusaf 5.0 Destination of Agricultural and Forest Land Use 2015 of the Province of Brescia' (https://www.geoportale.regione.lombardia.it/).

The thematic map of the seismic risk shows in which seismic zone the municipalities are located, based on the seismic zonation available on the Lombardy Regional Geoportal.

The thematic map of the hydraulic risk illustrates which parts of the territory are located in flood risk areas (sources: Hydrogeological Management Plan and Flood Risk Management Plan – Lombardy Regional Geoportal).

3. RESULTS AND DISCUSSION

Three different matrices were created for the three different types of water sources managed by Acque Bresciane, which are groundwater (wells), springs and lake water sources.

3.1. Hazardous events

Each risk matrix considered a list of possible hazardous events that vary depending on the type of catchment considered. Table 2 reports the hazardous events related to each water source type.

3.2. Climate-related hazardous events in the catchment risk matrix

Climate changes, by increasing flood and drought events, sea level, and water temperature, are projected to be a risk for groundwater and surface water-dependant systems, by negatively affecting water quality and quantity with an increase in pollution, salinization, and eutrophication (IPCC 2022). Examples of climate-related hazardous events can be found in the literature regarding WSPs (Rickert & van den Berg 2021).

In this study, catchment risk matrices were developed including the impact of climate change on water sources. Data supporting the entire risk analysis of each WSP refer to a time horizon of the last 5 years. However, exceptional events and incidents of interest that occurred before this period can be considered by the team to support the risk assessment.

Among the hazardous events, the following are closely linked to climate change since their likelihood of occurrence can increase if extreme climatic phenomena occur:

a. Water contamination or interruption due to infrastructure flooding after heavy precipitation events (for wells and lake intakes)
b. Temporary water availability decrease due to low rainfall (for wells, springs and surface waters)

Table 2 | Hazardous events related to the different water sources

Hazardous events	Catchment type: Springs	Groundwater wells	Lake water sources
Water contamination or interruption due to acts of vandalism	X	X	X
Temporary water availability decrease due to low rainfall	X	X	X
Water contamination or interruption due to infrastructure flooding after heavy precipitation events		X	X
Water contamination due to environmental pressure sources insisting on the catchment area	X	X	X
Aquifer contamination due to land use	X		
Water contamination due to product use in agriculture (e.g., fertilizers and pesticides)		X	X
Natural aquifer contamination due to geology (e.g., sulphates)	X	X	
Water contamination from reduced chemical species in deep lake water layers/groundwater		X	X
Water contamination caused by inadequate infrastructure	X	X	X
Decrease of water source quality due to algal blooms			X
Temporary excluding of the spring due to high turbidity	X		
Circuit interruption or variation due to geological phenomena	X		
Water contamination or interruption due to biofouling (damage to the intake structure/sub-lacustrine pipeline/pumping station and deterioration of the quality of the water source)			X
Water quality deterioration or availability decrease due to structure damage or malfunction	X	X	
Interruption of water supply to users due to pump break or damage		X	X
Interruption of water supply to users caused by power outage		X	X

c. Temporary exclusion of the spring due to high turbidity (for springs)
d. Circuit interruption or variation due to geological phenomena (for springs)
e. Water contamination or interruption due to biofouling (for lake intakes)
f. Decrease of water source quality due to algal blooms (for lake intakes)

Events *b* and *c* affect the quantity of the water resource, *f* affects its quality, while *a, d*, and *e* affect both quantity and quality.

The hazardous event 'water contamination or interruption due to infrastructure flooding after heavy precipitation events' refers to the effect of extreme rainfalls on catchment facilities. The characteristics that have an impact on this event are the following technical construction characteristics recorded in the checklists during site inspections:

- Position of the wellhead or pumping station in relation to ground level: If below ground level, the infiltration of rainwater into the well/lake intake is much more likely, causing possible water contamination (e.g., turbidity).
- Position of the electrical panels in relation to ground level: If below ground level, there is a greater likelihood that the electrical panels will be out of use in case of a flooding event.
- Waterproofing of the structure: If the structure is waterproofed, the likelihood of infiltration is low.
- State of maintenance of the infrastructure: If the state of maintenance of the infrastructure is not optimal, the likelihood that flooding affects water quantity and/or quality is high.

Another characteristic to be considered for the flooding event is the hydraulic risk, so it is important to check if the catchment is in a high hydraulic risk area, by using the relative thematic map.

The hazardous event 'temporary water availability decrease due to low rainfall' is related to the occurrence of drought seasons. The characteristics affecting this event are reported as follows:

- The catchment is the only and/or the main available water source: If there are no alternative water sources, there is a high likelihood of not providing a water supply service to users.
- Spring/summer drought periods in the last six years: If 'yes', there is a high likelihood of not providing a water supply service to users.
- Autumn/winter drought periods in the last six years: If 'yes', there is a high likelihood of not providing a water supply service to users.

Drought periods refer to unusually dry weather conditions caused by low rainfall and high temperatures. Moreover, an important factor to be considered is the water demand, since it can increase the impact on water availability during drought periods.

The hazardous event 'temporary exclusion of the spring due to high turbidity' is linked to the occurrence of heavy precipitation events that may generate an increase in turbidity parameter value in spring waters. The only characteristic of the risk matrix that can influence its likelihood is the occurrence of turbidity increase events in the last 5 years.

The hazardous event 'circuit interruption or variation due to geological phenomena' refers to the change in the spring paths within rock matrices. The mountainous landscape where fractured aquifers are located is exposed to landslide risk, as well as seismic risk. The system of fractures in which the aquifer flows may be damaged by landslides and/or earthquakes, resulting in the interruption or modification of groundwater paths and leading to alterations in well performance and/or in water quality, since the new circuits may generate new pollutants. The characteristics that can impact this event are the following:

- Landslide risk: If the area where the spring is located is classified as actively unstable, the likelihood of occurrence of modified or interrupted circuit increases. Climate change has an impact on this event since it raises the frequency of rainfall periods, which increase the likelihood of landslides on hillsides. Rainfall periods are projected to increase in central Europe, by up to one more period per year in flat areas in low altitude and by up to 14 more periods per year at higher altitudes by mid-century and increasing its evidence by the end of the century (Schlögl & Matulla 2018; Ranasinghe *et al.* 2021).
- High seismic risk: If the spring is located in a high seismic risk area, the likelihood of changing circuit or stopping is higher, because the likelihood of occurrence of seismic phenomena is higher.

The hazardous events 'water contamination or interruption due to biofouling' and 'decrease of water source quality due to algal blooms' regards lake water sources and the characteristics that can influence these events are the following:

- trophic level of the lake;

- position of the lake intake in relation to the euphotic zone;
- positioning and configuration of the intake.

Harmful algal blooms (proliferations of phytoplankton and macroalgae) has increased since the early 1980s, in response to warming, deoxygenation, and eutrophication, with an impact on human health depending on species-specific responses to the interactive effects of climate change and other human drivers, for instance, pollution (IPCC 2019). The effect of climate change may act to make algal blooms become more frequent and intense, so that advances in their prediction will be needed to formulate plans that minimize their impacts on coastal ecosystems and human communities (Gobler 2020).

Other characteristics related to biofouling are the state of maintenance of the protection grid of the intake structure and of the sub-lacustrine pipeline, the slope management and the state of maintenance of the pumping station.

3.3. Application of the thematic maps for the likelihood calculation

Figure 2 shows an example of the environmental pressure sources map. Table 3 shows an extract of the risk matrix related to the environmental pressure sources, especially showing the categories that the user should select considering the map (Figure 2). Therefore, if the map shows that there are environmental pressure sources in the catchment protection zone, the related lines of the risk matrix (Table 3) should be compiled. In this example, there is a contaminated site in the buffer zone; thus, the 'x' symbol is put in the column 'category checkbox' at the related line 'contaminated or de-contaminated sites' in Table 3.

Figure 3 shows an example of the thematic map of the land use, showing the land use of the territory in which the specific drinking water catchment is located. This map enables the user to assess which type of land use is present in the buffer zone of the catchment and consequently allows the user to compile the corresponding lines of the risk matrix (Table 4). In this case,

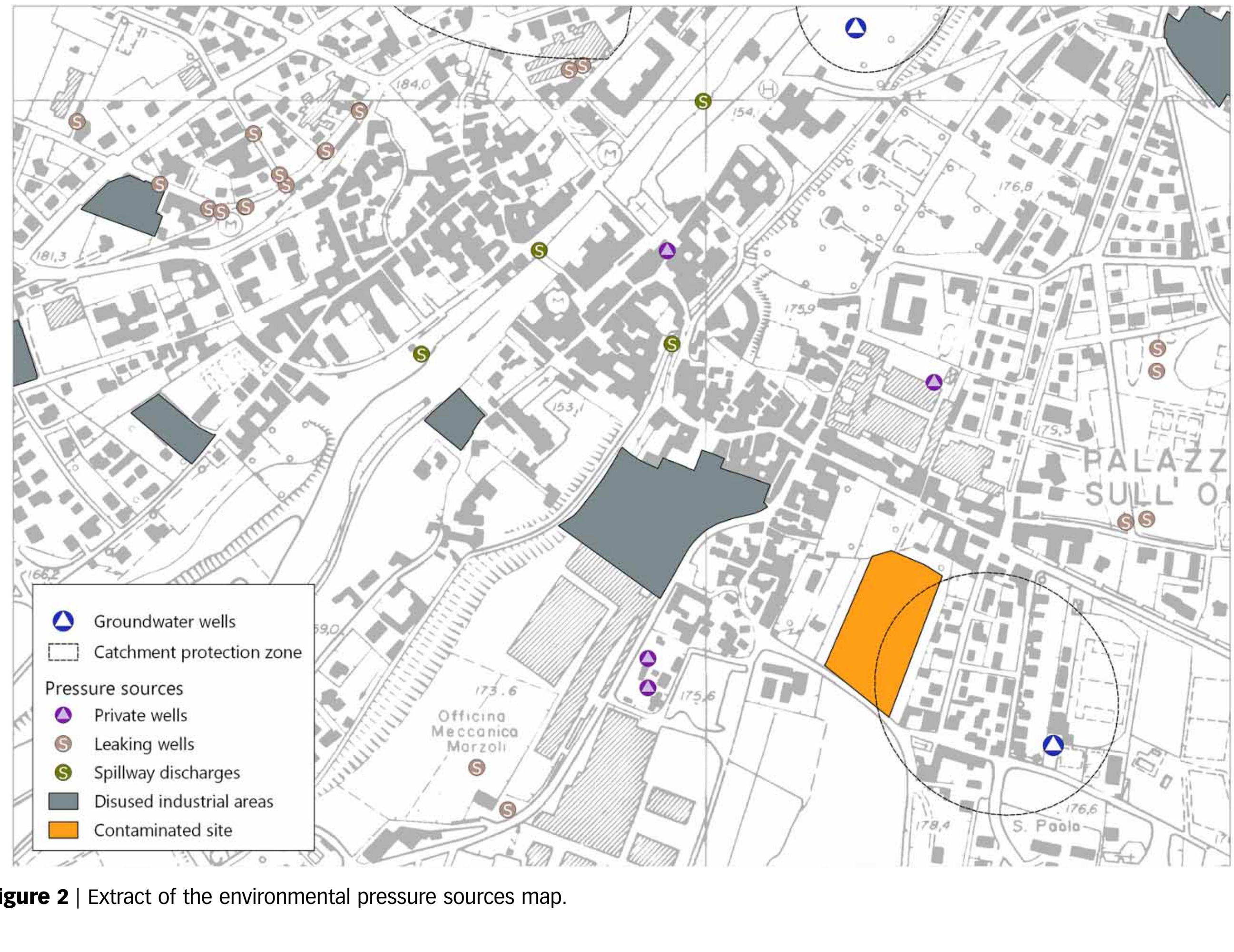


Figure 2 | Extract of the environmental pressure sources map.

Table 3 | Risk matrix extract regarding environmental pressure sources (example related to Figure 2)

Aspect	Reference documents	Characteristic	Category	Value	Category checkbox	Corresponding value	[...]
Buffer zone	Environmental pressure sources map	Pressure sources	Not present	1		5	[...]
			Disused wells	3			
			Private wells	4			
			Leaking wells (rainwater)	4			
			Wastewater treatment plants discharges	4			
			Livestock/grazing lands	5			
			Mountain pastures	5			
			Cemeteries	5			
			Mining activities	5			
			Industries with significant accident hazard	5			
			Landfills	5			
			activities required by integrated environmental authorization (not included in the other categories)	5			
			Contaminated or de-contaminated sites	5	X		
			Untreated discharges	5			
			Wastewater treatment plants bypass discharges	5			
			Emergency discharges	5			
			Spillway discharges	5			
			Demolition centres/storage areas	5			
[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]

Figure 3 | Extract of the land use map.

Table 4 | Risk matrix extract regarding land use type (example related to Figure 3)

Aspect	Reference Documents	Characteristic	Category	Value	Category checkbox	Corresponding value	[…]
Buffer zone	- Catchment source checklist - Land use map	Land use type	Residential	1		5	[…]
			non-agricultural green	1			
			Water bodies	1			
			Wetlands	2			
			Extractive	2			
			Productive (industries/hospitals/ cemeteries/railways…)	3			
			Agricultural	5	X		
[…]	[…]	[…]	[…]	[…]	[…]	[…]	[…]

the land use in the buffer zone of the catchment is mainly agricultural; therefore, the 'x' symbol is put in the column 'category checkbox' at line 'agricultural' in Table 4.

Figure 4 shows an example of the thematic map of the seismic risk that illustrates the seismic zonation of the area object of study. This information is then reported in the section 'hydrogeological characteristics' of the risk matrix. In this example, the municipality object of study, with border highlighted in blue, is in 'zone 2,' and consequently, the 'x' symbol is put in the column 'checkbox category' at line 'yes' in Table 5.

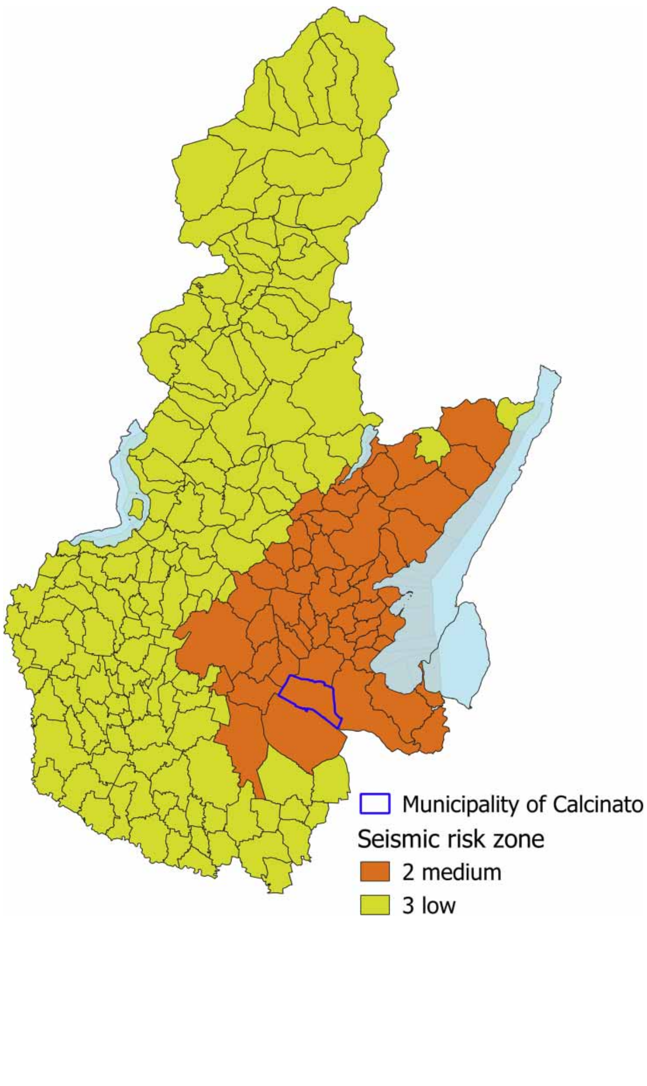


Figure 4 | Seismic risk map.

Table 5 | Risk matrix extract regarding high seismic risk zone (example related to figure 4)

Aspect	Reference documents	Characteristic	Category	Value	Category checkbox	Corresponding value	[...]
Hydrogeological characteristics	Seismic risk map	Municipality in high seismic risk zone (according to Lombardy region zoning)	No Yes	1 5	 X	5	[...]
[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]

Figure 5 shows an example of the thematic map of the hydraulic risk that illustrates the presence of river belts and flood hazard areas in the territory under analysis and allows the user to check if there are catchments located in high hydraulic risk areas. Table 6 presents an extract of the risk matrix part where information about hydraulic risk is reported. In this case, a groundwater well (marked by the arrow in Figure 5) is in 'H – frequent floods' area; therefore, in the specific matrix of that well, the symbol 'x' is put in the column 'checkbox category' at line 'yes' (Table 6).

As already explained in Section 2.2.1, column 7 (named 'corresponding value') automatically calculates and reports the corresponding value (from 1 to 5) based on the choice made in column 6. In the case of multiple choices in the 'checkbox category' column, the formula implemented in column 7 calculates the highest value among those selected (Table 3).

3.4. Hydrodynamic and hydrochemical characterization of the aquifers

The hydrogeological and environmental characteristics reported in the catchment matrices were compiled after a specific research study on the hydrodynamic and hydrochemical characterization of the catchments, developed by DISAT of

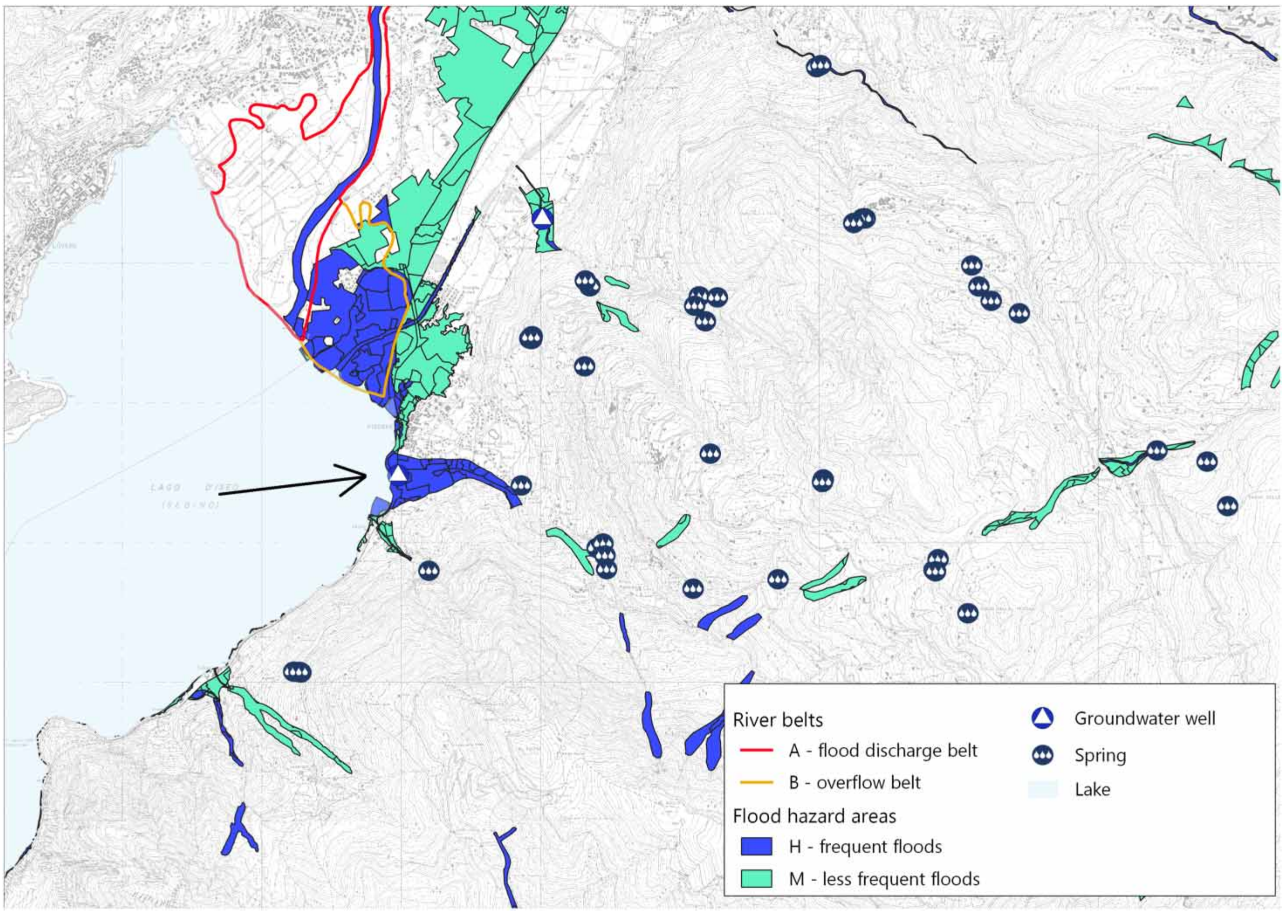


Figure 5 | Extract of the hydraulic risk map.

Table 6 | Risk matrix extract regarding high hydraulic risk zone (example related to Figure 5)

Aspect	Reference Documents	Characteristic	Category	Value	Category checkbox	Corresponding value	[...]
Infrastructural characteristics	Hydraulic risk map	Presence of high hydraulic risk in the water catchment area	No Yes	1 5	 X	5	[...]
[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]

University of Milano Bicocca. The hydrodynamic characterization of the catchments was carried out analysing a 16-year dataset of static and dynamic piezometric levels measured by Acque Bresciane in its 183 groundwater wells from 2006 to 2021. Data were grouped and processed based on territorial subdivision into three hydrogeological compartments: plain compartment, Iseo morainic compartment, and Garda morainic compartment (Figure 6).

To perform the hydrochemical characterization, Acque Bresciane monitoring analysis (212˙143) were collected related to raw water at all catchment points from 2009 to 2019. Parameters of greatest interest were selected, namely, those representatives of the characteristics of water bodies present in the area and representatives of the main processes that may affect them (e.g., indicator parameters of spread contamination related to land use, redox-sensitive parameters related to reducing phenomena typical of the low plain aquifers). Overall, 21 parameters were selected: alkalinity, Al, NH4, As, bicarbonates, Ca, Cl, electrical conductivity, hardness, Fe, Mg, Mn, Ni, NO3, NO2, pH, Pb, K, Na, SO4, water temperature. Each well was classified, and its vulnerability was assessed (Zanotti *et al.* 2022). This classification allowed the compilation of the following characteristics of the WSP catchment matrices:

- captured aquifer type;
- aquifer depth;
- average permeability of unsaturated soil;
- residence time of the captured aquifer;
- groundwater circulation in naturally sulphate-releasing layers;
- natural redox conditions;
- trophic level of the lake;
- location of the euphotic zone.

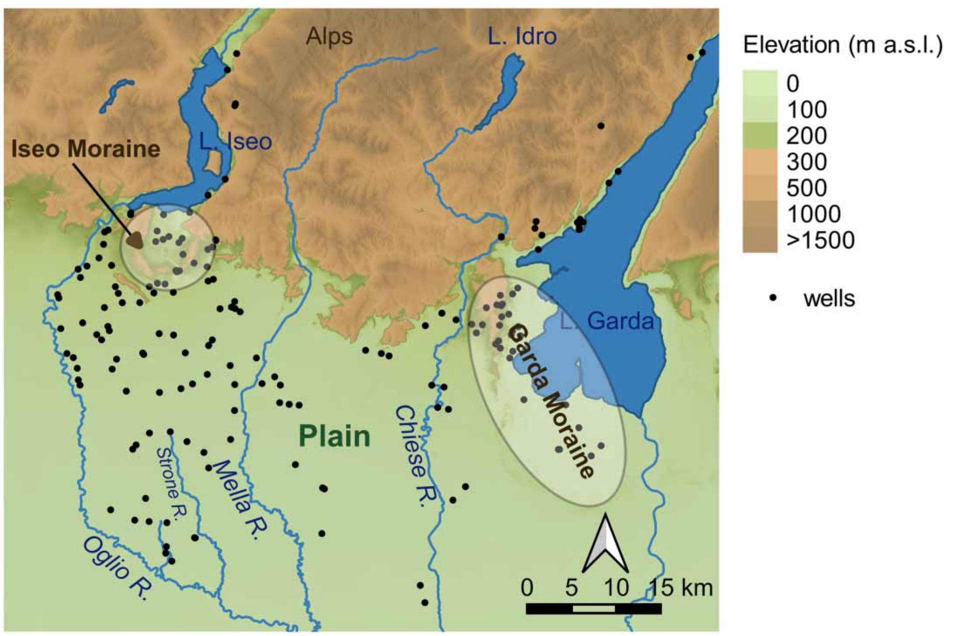


Figure 6 | Hydrogeological compartments studied in the province of Brescia (Italy) (Zanotti *et al.* 2022).

3.5. Control measures

To reduce the residual risks of climate change-related events, several control measures were suggested. Many of these control measures correspond to the actions of the water supply emergency plan of Acque Bresciane, developed to manage different emergency situations that could affect the drinking water supply system, including insufficient supply of water to users due to limited water availability as a result of drought scenarios.

The following control measures were suggested to reduce the likelihood of occurrence of the hazardous events: (a) water contamination or interruption due to infrastructure flooding after heavy precipitation events (for wells and lake intakes), (b) temporary water availability decrease due to low rainfall (for wells, springs, and surface waters), (c) temporary excluding of the spring due to high turbidity (for springs), (d) circuit interruption or variation due to geological phenomena (for springs), and (e) water contamination or interruption due to biofouling (for lake intakes), which may cause the hazard 'insufficient water supply':

- Use of alternative drinking water sources: To have an overview of the available water sources, the WSP team elaborated a map and a list of the alternative drinking water sources (wells, springs, and surface waters) that are always available in a specific archive, easily accessible and usable. In particular, these documents are saved in the emergency plan, with access to all the technicians and operators. In case the water utility decides to use an alternative source that has not been used for a long period or a private water source, the Health Protection Agency (ATS Brescia) must carry out the analytical check and decides if a temporary use can be approved until the end of the emergency.
- Construction of new well/intake according to the emergency procedure: If alternative sources are not available or cannot be used, a new catchment could be built according to the emergency procedure described in the general drinking water emergency plan. For instance, this control measure could be put in place when biofouling phenomena obstruct the lake catchment, compromising water availability;
- Use of tanker trucks: Storage tanks are immediately available if they already exist in the drinking water supply system, but if a system does not include tanks (e.g., wells that directly pump water to a distribution network), water tank trucks can be used in case of emergency. When developing WSPs, it is useful to provide, for drinking water systems where tanker trucks may be useful, a suitable intake point and the number of transports required. This control measure is especially adopted in mountain systems, where the increase in water consumption occurs during periods of spring flow reduction.
- Use of water bagging machine: The production of bags of drinking water using a bagging machine and their distribution to the users without a water supply at the tap is a control measure that can be implemented in replacement or in addition to the measure 'use of tanker trucks.'
- Interconnection between water supply systems: A good practice to prevent disservices to water users could be the interconnection of a water supply system to another in one or more points of the network with open or close valves, especially if the system does not include storage tanks or other available water sources.

The following control measures were suggested to reduce the likelihood of occurrence of the hazardous events: (a) water contamination or interruption due to infrastructure flooding after heavy precipitation events (for wells and lake intakes), (b) circuit interruption or variation due to geological phenomena (for springs), (c) water contamination or interruption due to biofouling (for lake intakes), and (d) decrease of water source quality due to algal blooms (for lake intakes), which may cause the hazards 'microbiological contamination' and 'chemical contamination'':

- installation of chemical (sodium hypochlorite or chlorine dioxide) or physical (UV) disinfection, for microbiological problems;
- installation of specific treatment plants if the contamination is caused by chemicals;
- maintenance or cleaning of the lake intake in case of biofouling;
- installation of specific treatment plants if the contamination is caused by algal bloom.

The WSP team also developed a specific emergency plan for each drinking water supply system, in addition to the general emergency plan of Acque Bresciane. This plan specifies the operations of all the water system facilities (water catchments, storage tanks, and drinking water treatment plants), and for each one, it reports the possible hazardous events that could occur and the control measures to be put in place to manage the related emergency. The WSP emergency plan also contains information regarding the presence of interconnections between water distribution networks, including cartographic extracts and calculations regarding the water availability of storage tanks, namely, the emptying times and alarm water levels by remote control.

3.6. Risk assessment case studies for the three catchment types

To better explain the development and the compilation of the risk matrix, three application cases are presented, one for each type of catchment. A groundwater well, a spring, and a lake water source are considered, each belonging to a specific drinking water system for which Acque Bresciane has already assessed a WSP and therefore developed the associated analysis sheets.

In detail, the sources analysed in the case studies are as follows:

1. a groundwater well called 'Gavazzino' of the drinking water supply system of 'Palazzolo sull'Oglio';
2. a lake water source called 'Porticcioli' of the drinking water supply system of 'San Felice del Benaco' (Garda Lake);
3. a spring called 'S.Vittore' of the drinking water supply system of 'Pisogne'.

3.6.1. Risk matrix application: groundwater well

The groundwater well 'Gavazzino' is located in the territory of Palazzolo sull'Oglio, a municipality located in the western plain of the Province of Brescia.

Before starting to compile the risk matrix, onsite inspections of the well were necessary to find out the conditions of the plant and to produce the related checklist. During the onsite inspections, photographs of every part of the plant were taken, to have a reference document, which could be useful if any doubt existed while compiling the analysis sheet of the catchment.

Moreover, the following documents were made before proceeding with the likelihood calculation:

- Spreadsheet that collects all the information concerning the well, such as the position of the filters, pump depth, static and dynamic level of the water table, diameter, etc.;
- Thematic maps (Section 2.2.3);
- Report that comes from the hydrodynamic and hydrochemical characterization of the aquifers (Section 3.4).

Once all these documents were available, it was possible to start with the compilation of the Gavazzino well analysis sheet (see Table 4S in the Supplementary Material).

The classification of the characteristics of Gavazzino well in the risk matrix analysis sheet is here illustrated by the following points:

- Absolute protection zone (information source: onsite inspections and checklist):
  - Type of access: adequately protect, value 1; the access is protected by a padlocked gate;
  - Conditions and dimensions: inadequate dimensions, value 2; conditions of the absolute protection zone are adequate, since there is no waste storage; instead, dimensions are inadequate because its radius is less than the required 10 m;
  - Waterproofing of the area: presence, value 1; the area is cemented;
- Buffer zone (information source: onsite inspections and checklist, pressure sources map, land use map, well information spreadsheet):
  - Type of delimitation criteria: temporal criteria, value 1; this information can be derived from concession documents of the well and reported in the well information spreadsheet;
  - Land use type: residential, value 1; this information can be deducted from land use map and verified during onsite inspection;
  - Pressure sources: not present, value 1; this information can be deducted from pressure sources map and verified during onsite inspection;
- Infrastructural characteristics (information source: onsite inspections and checklist, well information spreadsheet, hydraulic risk map):
  - Type of access of the well pumping station: adequately protect, value 1; the access is protected by a lockable door;
  - The well is the only and/or the main source of supply of the water supply zone: no, value 1; Gavazzino well is located in a water supply zone (defined in the WSP of Palazzolo sull'Oglio) where there are other two wells in operation;
  - Location of the wellhead in relation to ground level: below the ground level, value 5; Gavazzino wellhead and pumping station are located in a structure below the ground level;

  - Location of the electrical panels in relation to the ground level: below the ground level, value 5; electrical panels are located in the same place of the wellhead;
  - Presence of hazardous materials inside the well building: absence, value 1;
  - Presence of waterproofing of the upper well grout: presence, value 1; this information can be deducted from the stratigraphy made during the drilling activity of the well;
  - Presence of waterproofing of the well structure: presence, value 1; the roof covering and the flooring of well infrastructure are waterproofed;
  - Presence of systems to prevent animals from entering: absence, value 5; in some windows, there are no insect grids or there are insect grids with holes of unacceptably large dimension;
  - Overall assessment of the state of maintenance of the infrastructure: optimal, value 1;
  - Overall assessment of the condition of the upper well grout: suboptimal/unknown, value 5; this characteristic was classified as 'unknown' because a recent video inspection of the well is not available;
  - Presence of high hydraulic risk in the water catchment area: no, value 1; this information was taken from the hydraulic risk map;
  - Age of pump number 1: <8 years, value 1; information deducted from the well information spreadsheet;
  - Age of pump number 2: not present, value 0; Gavazzino well has just one pump;
- Hydrogeological characteristics (information source: seismic risk map, report about hydrodynamic and hydrochemical characterization of the aquifers):
  - Aquifer type (considering its influence on the occurrence of hazards of anthropic origin): unconfined, value 5;
  - Aquifer type (considering its influence on the occurrence of hazards of natural origin): unconfined, value 1;
  - Aquifer depth (evaluated only for unconfined or semi-confined aquifers): 20–40 m from ground level, value 3;
  - Average permeability of unsaturated soil (for unconfined aquifers) or of soil between first filter and ground level (for semi-confined aquifer): high, value 5;
  - Residence time of the captured aquifer (considering its influence on the occurrence of hazards of anthropic origin): short, value 5;
  - Residence time of the captured aquifer (considering its influence on the occurrence of hazards of natural origin): short, value 1;
  - Groundwater circulation in naturally sulphate-releasing layers: no, value 1;
  - Risk of landslide events in the water catchment area: no, value 1;
  - Municipality in high seismic risk zone (according to Lombardy region zoning): no, value 1;
  - Natural redox conditions: oxidizing, value 1.

All the information regarding the hydrogeological characteristics of Gavazzino well were obtained from the research project carried out by the team of the University of Milano Bicocca about hydrodynamic and hydrochemical characterization of the aquifers (Zanotti *et al.* 2022) and simply reported in the risk matrix, except for those related to seismic risk, resulting from the seismic risk map.

The likelihood values obtained for each hazardous event in the analysis sheet of the Gavazzino well are reported here:

- water contamination or interruption due to acts of vandalism: 1;
- water contamination or interruption due to infrastructure flooding after heavy precipitation events: 2.4;
- water contamination due to environmental pressure sources insisting on the catchment area: 3.2;
- water contamination due to product use in agriculture (e.g., fertilizers and pesticides): 3.2;
- natural aquifer contamination due to geology (e.g., sulphates): 1;
- water contamination from reduced chemical species in deep lake water layers/groundwater: 1;
- water contamination caused by inadequate infrastructure: 1.8;
- water quality deterioration or availability decrease due to structure damage or malfunction: 2.3;
- interruption of water supply to users due to pump break or damage: 1;
- interruption of water supply to users caused by power outage: 1.

These likelihood values were then used to calculate the related risks (not shown in this work), obtained as the product of the likelihood of occurrence of a single hazardous event, the severity (or consequences), and the detectability, with the following formula:

$$R = L \times S \times D$$

where R is the risk, L is the likelihood of occurrence of the hazardous event, S is the severity of the consequent hazard, and D is the detectability (which quantifies how many times the hazard has been recorded in the last 5 years). The risks are then classified into five categories, as follows:

- 1: [0–25) low risk;
- 2: [25–50) medium-low risk;
- 3: [50–75) medium-high risk;
- 4: [75–100) high risk;
- 5: [100–125] very high risk.

The risk calculation is based on the WHO guidelines on WSPs (WHO 2023).

The severity is a number from 1 to 5 that depends on the hazard:

- 1 no impact on water quality;
- 2 insignificant impact;
- 3 organoleptic impact;
- 4 chemical contamination;
- 5 microbiological contamination.

The detectability is a number from 1 to 5 based on the classification of the 95th percentile of a specific water quality parameter in the last 5 years. In particular, for each water quality parameter, the extremes of each class are calculated considering the limit of quantification of the parameter and the regulation limit.

For example, for pesticides, the classes are as follows:

- 1: $\leq$0.03 mg/L, which is the limit of quantification;
- 2: 0.04–0.06 mg/L;
- 3: 0.06–0.07 mg/L;
- 4: 0.07–0.09 mg/L;
- 5: $\geq$0.09 mg/L, (0.1 mg/L is the Italian regulation limit).

For example, considering the hazardous event 'water contamination due to product use in agriculture' with a likelihood of 3.2 and a registered pesticide concentration of 0.08 mg/L (as 95th percentile calculated in the last 5 years of monitoring), the severity of the hazard 'pesticide' is 4 considering that it is a chemical parameter causing potential long-term health effects and the detectability is 4; thus, the calculated risk is 51.2, which corresponds to a medium- to high-risk class.

3.6.2. Risk matrix application: lake water source

The lake water source 'Porticcioli' is located in the territory of San Felice del Benaco, a municipality located in the southern eastern part of Garda Lake, in the Province of Brescia.

As per the Gavazzino well, before starting to compile the risk matrix for the lake water source Porticcioli, the onsite inspections (including a photographic survey) and the development of the related checklist were carried out.

The following documents were prepared before proceeding with the likelihood calculation:

- Spreadsheet that collects all the information concerning the lake water source, such as radius length of the buffer zone, depth of the intake from the lake surface, distance of the intake from the lakeshore, pump age;
- Thematic maps (Section 2.2.3);
- Report that comes from the hydrodynamic and hydrochemical characterization of the lake water sources (Section 3.4).

Once all these documents were available, it was possible to start with the compilation of the Porticcioli lake water analysis sheet (Table 5S in the Supplementary Material).

The classification of the characteristics of Porticcioli lake water source in the risk matrix analysis sheet is here illustrated by the following points:

- Absolute protection zone (information source: onsite inspections and checklist):
  - Type of delimitation: properly marked (with buoy), value 1; the access is marked by the presence of a floating device;
- Buffer zone (information source: onsite inspections and checklist, pressure sources map, land use map, lake water source information spreadsheet):
  - Type of delimitation criteria: geometric criteria, value 2; this information can be derived from concession documents of the source and reported in the related information spreadsheet:
  - Land use type: water bodies, value 1; this information can be deducted from land use map and verified during onsite inspections;
  - Pressure sources: shipping lanes (ferries), port, value 3; this information can be deducted from pressure sources map and verified during onsite inspection; the two pressure sources found in the buffer zone have the same value, i.e., value 3;
- Infrastructural characteristics (information source: onsite inspections and checklist, lake water source information spreadsheet, hydraulic risk map):
  - The lake water source is the only and/or the main source of supply of the water supply zone: yes, value 5; Porticcioli is the only water supply source of the drinking water system of San Felice del Benaco;
  - Position and configuration of the lake water intake structure: adequate, value 1; Porticcioli lake water source has a depth of 42.53 m from the lake surface (lake bottom depth: 44.53 m), and it is situated 93 m from the lakeshore;
  - Presence of the protective grid on the water intake structure: presence, value 1;
  - State of maintenance of the protective grid on the water intake structure: optimal, value 1;
  - State of maintenance of the sub-lacustrine pipeline: optimal, value 1;
  - Type of access to the pumping station: adequately protected, value 1;
  - Location of the pump head in the pumping station in relation to the ground level (above or below the ground level): below the ground level, value 5;
  - Location of the electrical panels in relation to the ground level: above the ground level, value 1;
  - Presence of hazardous materials inside the pumping station: absence, value 1;
  - Slope management: presence, value 1;
  - Presence of waterproofing of the structure (pumping station): absence, value 5;
  - Presence of systems to prevent animals from entering in the pumping station: presence, value 1; presence of insect grids on the opening to the outside with proper hole dimension;
  - Overall assessment of the state of maintenance of the infrastructure (pumping station): suboptimal, value 5;
  - Presence of high hydraulic risk in the water catchment area: no, value 1; this information was taken from the hydraulic risk map;
  - Age of pump number 1: <8 years, value 1; information deducted from the lake water source information spreadsheet;
  - Age of pump number 2: ≥ 8 years, value 5; information deducted from the lake water source information spreadsheet;
  - Age of pump number 3: ≥ 8 years, value 5; information deducted from the lake water source information spreadsheet;
  - Age of pump number 4: ≥ 8 years, value 5; information deducted from the lake water source information spreadsheet;
- Ecological environmental characteristics (information source: lake water source information spreadsheet, report about hydrodynamic and hydrochemical characterization of the lake water sources):
  - Trophic level of the lake: oligotrophic, value 1;
  - Position (on the vertical) of the intake with respect to the euphotic zone: always below the euphotic zone, value 1;
  - Position (on the vertical) of the intake with respect to the mixing zone: always inside the mixing zone, value 5;
  - Time elapsed since the most recent complete mixing of the lake: >7 years, value 5;
  - Percentage depth of the intake (intake depth/lake bottom depth $\times$ 100): $>70\%$, value 3;
  - Distance (m) of the intake from the shore: 200–50 m, value 3; distance calculated on the orthogonal line from the intake to the nearest coastline.

All the information regarding the hydrogeological characteristics of Porticcioli lake water source were obtained from the research project carried out by the team of the University of Milano Bicocca about hydrodynamic and hydrochemical characterization of the aquifers (Zanotti *et al.* 2022) and simply reported in the risk matrix.

The likelihood values obtained for each hazardous event in the analysis sheet of the Porticcioli lake water source are reported here:

- Water contamination or interruption due to acts of vandalism: 1;
- Water contamination or interruption due to infrastructure flooding after heavy precipitation events: 3.6;
- Water contamination due to environmental pressure sources insisting on the catchment area: 2.9;
- Water contamination due to product use in agriculture (e.g., fertilizers and pesticides): 2.8;
- Water contamination from reduced chemical species in deep lake water layers/groundwater: 3;
- Water contamination caused by inadequate infrastructure: 1.8;
- Decrease of water source quality due to algal blooms: 1;
- Water contamination or interruption due to biofouling (damage to the intake structure/sub-lacustrine pipeline/pumping station and deterioration of the quality of the water source): 1.6;
- Interruption of water supply to users due to pump break or damage: 3;
- Interruption of water supply to users caused by power outage: 5.

These likelihood values were then used to calculate the related risks (not shown in this work), obtained as the product of the likelihood of occurrence of a single hazardous event, the severity (or consequences), and the detectability, with the same method described in Section 3.6.1.

3.6.3. Risk matrix application: spring

The spring 'S. Vittore' is located in the territory of Pisogne, a municipality in the Province of Brescia located in the north-eastern bank of Iseo Lake, in a territorial context that is mostly mountainous.

Before filling in the risk matrix of S. Vittore spring, as already seen for the other two case studies, the onsite inspections (including a photographic survey) and the development of the related checklist were carried out.

The following documents were prepared before proceeding with the likelihood calculation:

- Spreadsheet that collects all the information concerning the spring, such as radius length of the buffer zone, maintenance, and territorial context;
- Thematic maps (Section 2.2.3);
- Report that comes from the hydrodynamic and hydrochemical characterization of the springs (Section 3.4).

Once all these documents were available, it was possible to start with the compilation of the S. Vittore spring analysis sheet (Table 6S in the Supplementary Material).

The classification of the characteristics of S. Vittore spring in the risk matrix analysis sheet is here illustrated by points:

- Absolute protection zone (information source: onsite inspections and checklist):
  - Type of access: Not adequately protect, value 5; the access to the absolute protection zone is not bordered and protected;
  - Conditions and dimensions: Existing and adequate in terms of conditions and dimensions, value 1;
  - Waterproofing of the area: absence, value 5; the area is not cemented;
- Buffer zone (information source: Onsite inspections and checklist, pressure sources map, land use map, spring information spreadsheet):
  - Type of delimitation criteria: Geometric criteria, value 2; this information can be derived from concession documents of the spring and reported in the spring information spreadsheet;
  - Land use type: Agricultural, value 5; this information can be deducted from land use map and verified during onsite inspection;
  - Pressure sources: Grazing lands, value 5; this information can be deducted from pressure sources map and verified during onsite inspection;
- Infrastructural characteristics (information source: Onsite inspections and checklist, well information spreadsheet, hydraulic risk map):
  - The catchment is the only and/or the main source of supply of the water supply zone: Yes, value 5; S. Vittore is located in a water supply zone (defined in the WSP of Pisogne) where there are no other water sources;
  - Presence of hazardous materials inside the spring building: Absence, value 1;
  - Slope management: Presence, value 1;
  - Presence of waterproofing of the spring structure: Absence, value 5; the closed space that hosts the spring is not cemented and water infiltration from the outside is possible;

  - Presence of systems to prevent animals from entering: Presence, value 1; absence of not protected windows or opening to the outside from which animals can enter;
  - Overall assessment of the state of maintenance of the infrastructure: Optimal, value 1;
  - Presence of high hydraulic risk in the water catchment area: No, value 1; this information was taken from the hydraulic risk map;
- Hydrogeological characteristics (information source: seismic risk map, report about hydrodynamic and hydrochemical characterization of the aquifers):
  - Spring/summer drought events in the last six years: No, value 1;
  - Autumn/winter drought events in the last six years: No, value 1;
  - Presence of sulphates of natural origin: No, value 1;
  - Risk of landslide events in the spring area: No, value 1;
  - Municipality in high seismic risk zone (according to the Lombardy region zoning): No, value 1;
  - Vulnerability to surface anthropogenic impacts from site-specific studies: Medium, value 3;
  - Turbidity increase in the last 5 years: yes, value 5.

All the information regarding the hydrogeological characteristics of S. Vittore spring were obtained from the research project carried out by the team of the University of Milano Bicocca about hydrodynamic and hydrochemical characterization of the aquifers (Zanotti *et al.* 2022) and simply reported in the risk matrix, except for those related to seismic risk, resulting from the seismic risk map.

The likelihood values obtained for each hazardous event in the analysis sheet of the S. Vittore spring are reported here:

- Water contamination or interruption due to acts of vandalism: 5;
- Temporary water availability decrease due to low rainfall: 2.3;
- Water contamination due to environmental pressure sources insisting on the catchment area: 3.2;
- Aquifer contamination due to land use: 3.3;
- Natural aquifer contamination due to geology (e.g., sulphates): 1;
- Water contamination caused by inadequate infrastructure: 2.1;
- Temporary excluding of the spring due to high turbidity: 5 ;
- Circuit interruption or variation due to geological phenomena : 1;
- Water quality deterioration or availability decrease due to structure damage or malfunction: 1.

These likelihood values were then used to calculate the related risks (not shown in this work), obtained as the product of the likelihood of occurrence of a single hazardous event, the severity (or consequences), and the detectability, with the same method described in Section 3.6.1.

3.7. Possible limitations of the tool

There are possible tool limitations that the WSP team should consider before starting the risk assessment. A possible difficulty could be the lack of data, such as the infrastructural characteristics of the catchment or the environmental data for the creation of the thematic maps. In the present case study, the technical data were available from the water utility and the environmental data were available from the Regional Geoportal or were easily provided by the Regional Environmental Protection Agency (Section 2.2.3), but some water utilities could find difficulties in collecting these data, especially in cases of old plants without documentation or if there is not a good collaboration with the local environmental authority. Sometimes, for example, missing data can be provided by other institutions, such as the municipal technical office. It is therefore important to involve all actors in the WSP team that can give useful contribution to the project, and it is important to ensure that each WSP team member will constantly collaborate providing information or data useful for the risk assessment. For example, during the first team meetings, a document could be created specifying the role of each team member, the contact information, and the possible contributions. In case of a lack of data, the team should plan to fill the gaps specifying for example required data, activities, required personnel, costs, schedule, etc. in the WSP improvement plan.

Another difficulty could be the definition of all the possible hazardous events. The WSP team should create a first list of events, but it is important to update it in case other events happen or have to be reconsidered by the team in future revisions of the risk assessment. For example, if a water utility only manages groundwater sources, but in the second revision of the WSP, a new drinking water source from a lake is introduced, the hazardous events related to lake sources should be added. The present work does not show an exhaustive list of hazardous events, because it is related to the WSP of a specific water utility; therefore, each WSP team should create its own list discussing and improving it during team meetings.

A possible difficulty could also be the definition of the probability of occurrence of the hazardous events and the definition of the control measures to reduce the residual risks. In this work, a specific calculation of the likelihood is suggested (Section 2.2.1), and possible control measures are proposed (Section 3.6), but it is recommended to discuss the method during the WSP team meetings, to define a calculation method that is as objective as possible, avoiding subjective assignment of the likelihood of occurrence, and to define the control measures considering the available resources and the characteristics of the territory. It is recommended to ensure the multidisciplinary nature of the WSP team, to allow an effective and constructive discussion about these topics.

Other difficulties could be found in identifying possible impacts of the hazardous events, and therefore, it could be useful to start from a first list as shown in this work (Section 3.2) and discuss it within the WSP team meetings, with the suggestion to upgrade and improve it also during subsequent WSP revisions.

Difficulties could be also found in defining the hydrogeological and environmental characteristics. In particular, it is important to have static and dynamic piezometric levels of the groundwater wells and the main hydrochemical characteristics, but sometimes the water utilities do not have these data. Therefore, it is strongly recommended to involve in the WSP team the local environmental protection agency that could provide these data. If other institutions could not provide the water levels and analysis, it could be useful for the water utility to plan and carry out a specific monitoring campaign to collect these data, to have a first overview of the hydrogeological and hydrochemical main characteristics of the groundwater wells. In general, it could be useful to also involve in the WSP team experts in the field of hydrogeology, such as professionals or researchers from the university.

4. CONCLUSIONS

This work described a simple and effective tool that can be applied by drinking water utilities to evaluate catchment risk with particular focus on climate-related hazardous events in the framework of WSPs. The WSP team of the Italian water utility Acque Bresciane, in collaboration with the University of Milano Bicocca, developed three catchment risk matrices, respectively, for wells, springs, and surface waters, with the aim of calculating the likelihood of occurrence of the hazardous events. The matrices were created by using the software Excel and can be replicated for each drinking water supply system. Specific thematic maps were created by using the software QGIS and were used to compile some parts of the matrices. Possible control measures were suggested to reduce risks in terms of water quality and availability and to respond with resilience to changes.

This tool has been developed to let any WSP team adapt it to the different water source types. Indeed, it is possible to easily modify each field of the risk matrix, i.e., aspects, characteristics, category, and it is possible to add or delete hazardous events, depending on the needs of the environment under analysis. These modifications can be implemented over time depending on the evolution of the features of the managed water supplies, e.g., environmental, hydrogeological, climatic variations of the context, or technical and structural evolutions of the facilities.

The risk matrix was conceived to fit the nature of the WSP, a dynamic tool that must follow the evolution of a water system over time. For this reason, the values assigned to each category and their respective weights can be updated over time, after discussion within the team.

Moreover, since the risk matrix is based on an objective analysis and can be replicated for all the water systems, it allows a comparison of the results obtained by each system to which it is applied, so that an overview of all managed systems can be obtained.

With regard to climate change, since this is a developing scenario, the risk matrix, due to its dynamic nature, allows an easy adaptation to include any new critical aspects that may occur in the future, as a result of the worsening of certain extreme climatic conditions.

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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