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Water safety planning for healthcare facilities for extreme events

Steffen Krause[a,*], Elena Joel[a], Christian Schaum[a], Jan Bäumer[b], Nadine Rücker[b], Ina Wienand[b], Christoph Sturm[c], Bernhard Jahn-Mühl[c], Manuel Geiger[d], Alexander Fekete[d], Sophie van der Heijden[e], Christine Heinzel[e] and Simone Sandholz[e]

[a] Sanitary Engineering and Waste Management, University of the Bundeswehr Munich, Neubiberg, Werner-Heisenberg-Weg 39 85577, Germany
[b] Directorate II – Risk Management, International Affairs, Division II.4 - Risk Management CI and CIP Concepts, Emergency Preparedness (Water), Federal Office of Civil Protection and Disaster Assistance, Postfach 1867, Bonn 53127, Germany
[c] AGAPLESION HYGIENE – Institute for Hygiene and Environmental Medicine, Ginnheimer Landstraße 94, Frankfurt am Main 60487, Germany
[d] TH Köln – University of Applied Sciences, Institute of Rescue Engineering and Civil Protection, Betzdorfer Straße 2, Cologne 50679, Germany
[e] United Nations University – Institute for Environment and Human Security (UNU-EHS), UN Campus, Platz der Vereinten Nationen 1, Bonn 53113, Germany
*Corresponding author. E-mail: steffen.krause@unibw.de

SK, 0000-0001-8075-6251

ABSTRACT

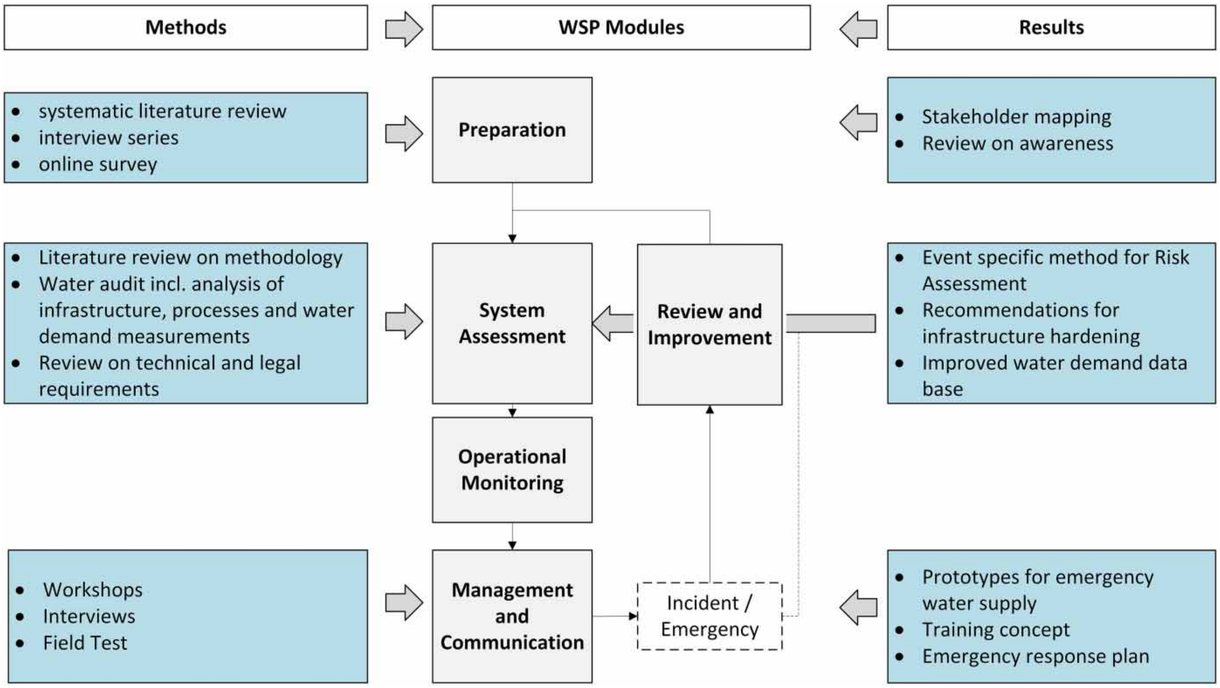
Disasters such as the Ahr Valley flood in 2021 make us aware of the importance of functioning healthcare facilities. Their functionality depends on the availability of drinking water. Water safety planning is a long-established method to increase the safety of water utilities. Our work supports the implementation of water safety planning in healthcare facilities during normal operations and emergency situations concerning the water supply. The authors conducted a stakeholder mapping exercise and problem awareness analysis. Based on these results, it was identified what is needed to overcome barriers to water safety planning (WSP). Building on existing procedures, the WSP concept, and latest scientific findings, an event-specific risk assessment method for healthcare facilities was developed and applied in a case study. Based on an analysis of water demand, water-related processes, and infrastructure, potentially necessary components for establishing an emergency supply were identified. For these, based on technical and legal requirements, planning principles were developed, and prototypes of components for emergency water supply were built. They were tested in pilot trials, particularly regarding hygienic safety. For the management of crises in hospitals, a survey was carried out on the command structures used in practice. Finally, recommendations were drawn based on the German Hospital Incident Command System.

Key words: drinking water impairment, emergency preparedness planning, healthcare facilities, risk assessment, sanitation impairment

HIGHLIGHTS

- Detailed insights into the requirements of hospital water supply including stakeholder mapping.
- Development of a methodology for an event-specific risk assessment supported by provision of an Excel-based tool.
- Presentation of an emergency response plan and an exercise concept for securing the water supply of hospitals.
- Development of technical components for the various processes of water supply in emergencies.

GRAPHICAL ABSTRACT



INTRODUCTION

Hospitals are considered critical infrastructure and play an important role in providing medical care to the population during ordinary and emergency situations. However, it is not only the medical equipment and personnel that are crucial for the functioning of hospitals but also the availability of safe and clean drinking water (Bross *et al.* 2019).

In addition to drinking and sanitation purposes, water is a prerequisite for hygiene and medical applications. However, there is often a lack of awareness regarding the probability and impact of an impairment of the water supply. The status of public water supply in industrialized countries such as Germany leads to a prevention paradox, where failures of the water supply are considered unlikely, resulting in lack of willingness to invest in precautionary measures.

The revised German Drinking Water Ordinance 2023, which is based on the EU Drinking Water Directive 2020/2184, makes risk management mandatory for public water supply companies, which should include all processes from treatment, storage, and distribution in addition to the catchment area. But still, there is no legal requirement for WSPs and emergency preparedness plans for healthcare facilities regarding water supply impairments. The existing state hospital laws in Germany also only implicitly address the issue of water supply.

This deficiency is reflected in the current state of knowledge on the status of emergency preparedness planning (van der Heijden *et al.* 2022). Furthermore, few publications exist on the water safety plan (WSP) for hospitals in high-income countries. This lack of knowledge was also the origin of the project 'NOWATER,' the results of which are partially presented here, and which was funded by the German Federal Ministry of Education and Research (BMBF).

As hospitals are considered as 'critical infrastructure,' there is a strong need to provide continuous medical services in the event of an emergency so both emergency preparedness and incident management planning are urgently recommended. Therefore, hospitals should prioritize the implementation of an Incident Command System (ICS). In Germany, there is an official recommendation by the Federal Office of Civil Protection and Disaster Assistance (Kowalzik *et al.* 2020) for the Hospital Incident Command System (HICS), advising hospitals to use the hospital Incident Management Team (HIMT), which is based on the incident command staff used by emergency services, described in the Fire Service Regulation 100 (AFKzV 2007). The HIMT structures and procedures therefore have been transposed from the Fire Service Regulation, barely been adapted, and evidence for suitability is not recognizable.

During ordinary operations, all water supply-related processes, including the management of failures, are effectively controlled by established means of operation and organizational structures. In contrast, extreme events, as defined herein based on DIN EN 15975-1 (2016), are events that seriously affect drinking water supply and which may require as a response other organizational structures and possibly more than usual means of operation, such as, for example, collaboration with emergency services. This definition can be linked to other common terms in risk management, natural hazards, and climate science, such as climate extremes, extreme weather events, or hazardous events, which would ultimately impact on water supply. In Germany, the allocation of responsibility for responding to such events depends on the scale of the incident in terms of damage and impact. If the cause is localized at the hospital premises, the hospital bears the responsibility. Conversely, events originating from the public water supply or exhibiting an extent of damage on local or regional level may shift responsibility to the water supplier or even the municipality.

The results of the project aim to strengthen the implementation of WSPs in hospitals including scenarios beyond ordinary operations by providing a detailed method for risk assessment (RA) in healthcare facilities. This method is closely aligned with WSP modules described in the World Health Organization's (WHO) Water Safety Plan Manual (WHO 2023) with an emphasis on the assessment of the system with a risk perspective (modules 2–4), planning improvements (module 5), as well as planning operational monitoring and verification programs (modules 6–7). Identifying organizational and technical measures for risk minimization, as well as recommendations for emergency planning and crisis management represent specifications of the modules 'Strengthening Management Procedures' (module 8) and 'Planning for Improvement' (module 5).

Furthermore, we provide recommendations for infrastructure hardening and processes as an essential part of risk minimization and crisis management. The successful implementation of these measures will ensure the availability of safe and clean water in hospitals, thereby contributing to the effective functioning of critical infrastructure during both ordinary and emergency situations.

METHODS

This publication includes data from an interview series and online surveys, to understand and analyze the context of preparedness and response measures for water supply outages and impairments within a number of German healthcare facilities. A total of 22 interviews with experts from healthcare facilities and related critical infrastructures in Germany were conducted between May 2021 and April 2022. Areas of expertise included technology ($n = 6$), hygiene ($n = 6$), medicine ($n = 4$), emergency preparedness and response ($n = 4$), and risk management ($n = 1$). The semistructured interviews focused on the four overarching topics of risk awareness, actors and responsibilities, emergency preparedness, and response. All interviews were transcribed verbatim and subsequently analyzed using a qualitative content analysis approach. The first online survey was conducted between May and July 2022, composed of a total of 33 questions covering the same topics as the interviews. Interviews were conducted in German or English and quotations used in this article were translated where necessary. The questionnaire was distributed to all healthcare facilities listed in the database of the German Federal Statistical Office (Statistisches Bundesamt 2021) and sent to the newsletter of one of Germany's largest hospital operators. The majority of participants worked in a hospital (59%) or in a rehabilitation center (21%). Remaining participants were employed in a medical care center (7%), nursing facility (7%), a physician's office (1%), or other unspecified healthcare facilities (4%). A potential limitation of the study is that people may have responded to the interview or survey questions with little or no expertise, which could have led to response bias; however, as participation was voluntary, this risk can be considered as relatively low.

The second survey was conducted between November 2022 and 15 February 2023 and then relaunched from 15 March 2023 to 30 April 2023 in a second round to generate a larger sample. It was distributed in the same method as the first survey but additionally distributed by the National German Hospital Federation, three German state hospital federations, and one private hospital association. The focus of the second survey was the HICS as well as the frequency and the type of training exercises for HIMT. This questionnaire consisted of 17 questions in total, including 6 questions about the hospital's characteristics, 3 questions about the HICS and HIMT in usage, and 8 questions about the number and types of training provided. In the first round, the survey was started 158 times, completed 76 times, and led to 67 usable participations after analysis and the elimination of doublings. In the second round, an additional 10 participants started the survey, leading to 5 usable datasets totaling 72 participations, which were used for the analysis.

As part of the development of an RA methodology for the impairment of water supply and sanitation in healthcare facilities, a comparison of existing procedures and guidelines (e.g., WSP and J100-10) was conducted with regard to their applicability in this specific context. This revealed the need for an event-specific modification and extension of existing approaches under consideration of the latest scientific findings. In the next step, the developed approach for RA was evaluated using data from practice partners. Furthermore, minimum requirements and necessary measures or combinations of measures were derived within the framework of emergency planning.

In addition, a survey of the water-related technical infrastructure at a sample hospital was conducted. This hospital was chosen as the subject of study because it was composed of a variety of medical equipment, buildings, and services. This provided the opportunity to generate a broad database that can be used for planning in numerous and diverse healthcare facilities. The hospital provides specialized care and has approximately 830 beds and 1,500 employees. The hospital's annual water consumption is about 70,000 m^3. The survey was conducted between January 2021 and April 2023 and included reviewing and updating piping plans for potable water, hot water, and wastewater. Water demand measurement campaigns were conducted in 1-week increments assessing different buildings and functional units in each case with four portable clamp-on ultrasonic flowmeters 'deltawaveC-P' from Systec controls. Ultrasonic clamp-on devices were chosen because their installation does not require the cutting or drilling of pipes; however, it was necessary to temporarily remove their insulation. Data were recorded at 10 s intervals and aggregated into hourly and daily values.

The measurement campaigns were designed to be transferable to other hospitals with different ranges of services. Also, the required water quality and the need for further treatment (softening, reverse osmosis) were surveyed. To facilitate the transferability to other healthcare facilities, the number of beds installed, bed occupancy, number of patient days, the number of sterilization units, the knife to skin time, and the number of surgeries were used for the normalization of water demand data.

Based on the information collected on water usage, processes in the hospital, minimum requirements, and possible combinations of measures, it was determined which technical components could be used for the provision of water in an emergency and what properties they would need to have. The technical components were designed for a maximum application period of 30 days. The requirements of the German Drinking Water Ordinance (BMG 2021) and the DVGW regulations (German Technical Association for Gas and Water) were taken as a basis for design as well as the quantitative and qualitative requirements caused by the medical devices and patient safety. They may be even higher in some cases. Consequently, the process design and materials of the technical components were selected to meet drinking water quality requirements. Beyond these requirements, the design of the technical components and the choice of materials considered that the devices can be put into operation quickly and operated hygienically even after long storage periods. The use of personnel and hazardous substances for cleaning and operation purposes should be as low as possible. To ensure compatibility with available vehicle equipment within municipalities, typical municipal vehicle inventory was also considered.

RESULTS

The results presented here are contributions to the different modules of WSP and support its implementation in healthcare facilities. Figure 1 illustrates which of the results can be assigned to which module.

Awareness and stakeholder mapping

A systematic literature review on emergency water supply for healthcare facilities showed an overall lack of literature on the subject. Of the 39 studies identified, only 17 focused on preparedness. Only five different types of emergency water supply plans for healthcare facilities were found. The importance of awareness raising to enable better preparedness was insufficiently addressed in the literature around emergency supply. The few sources that mention this issue focus primarily on concrete technical preparedness measures. Awareness was, if at all, only vaguely described as important for water suppliers (e.g., to know the emergency water needs of the healthcare facility) and patients (e.g., to be involved in the preparedness stage).

The survey conducted with German healthcare facilities revealed that the lack of knowledge and awareness toward water supply impairment is an important barrier to prepare for emergencies (Figure 2). This lack of knowledge and awareness contributes to potential threats to the infrastructure, the healthcare facility's water demand, existing emergency preparedness measures, and responsibilities in assessment and planning processes.

The lack of knowledge and awareness related to the vulnerabilities of the water supply and healthcare systems to hazardous events, and the responsibilities of key stakeholders in emergency preparedness and response were also perceived as one of the main barriers to emergency preparedness in the interview series. This lack of awareness could have direct consequences on preparedness and response, e.g., by reducing the financial budget or other resources to adapt.

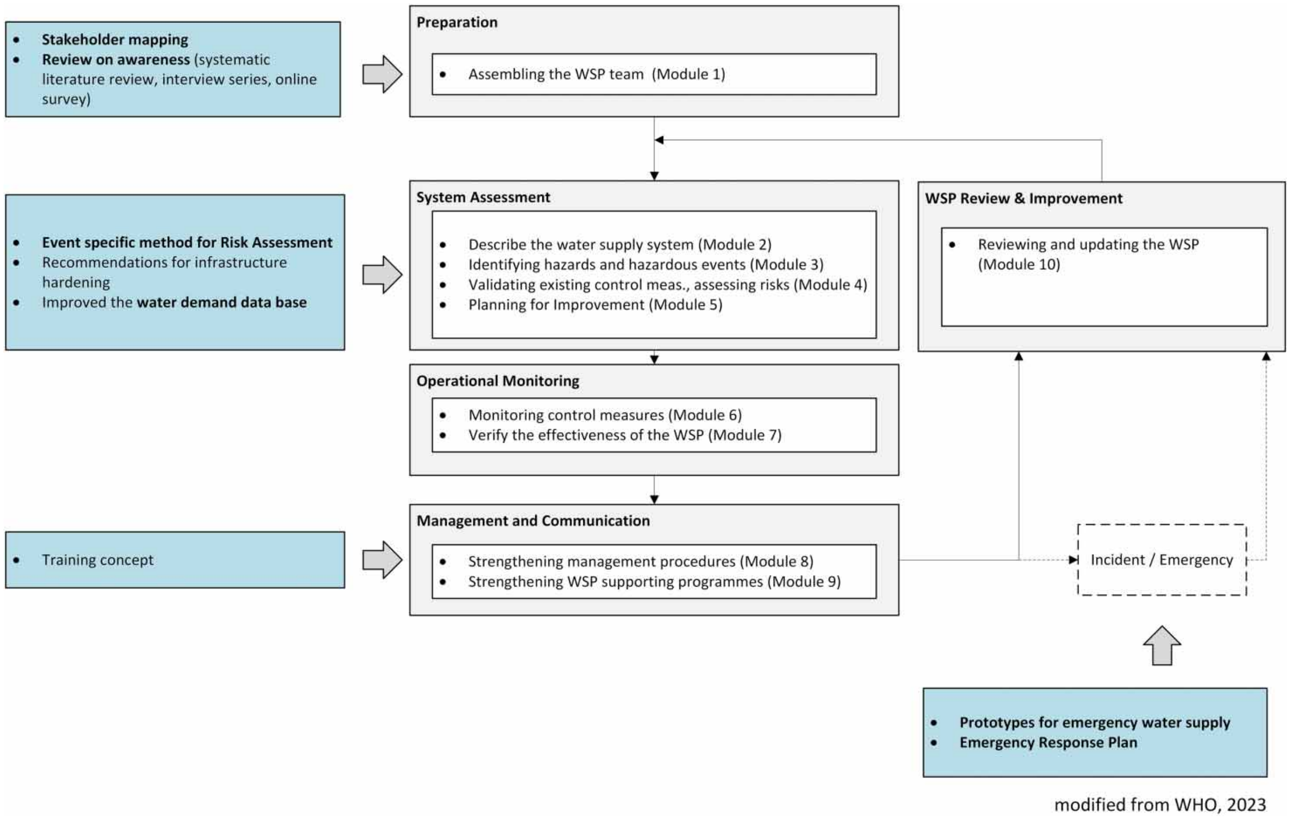


Figure 1 | Contributions (in blue) to the WSP process and main results (in bold).

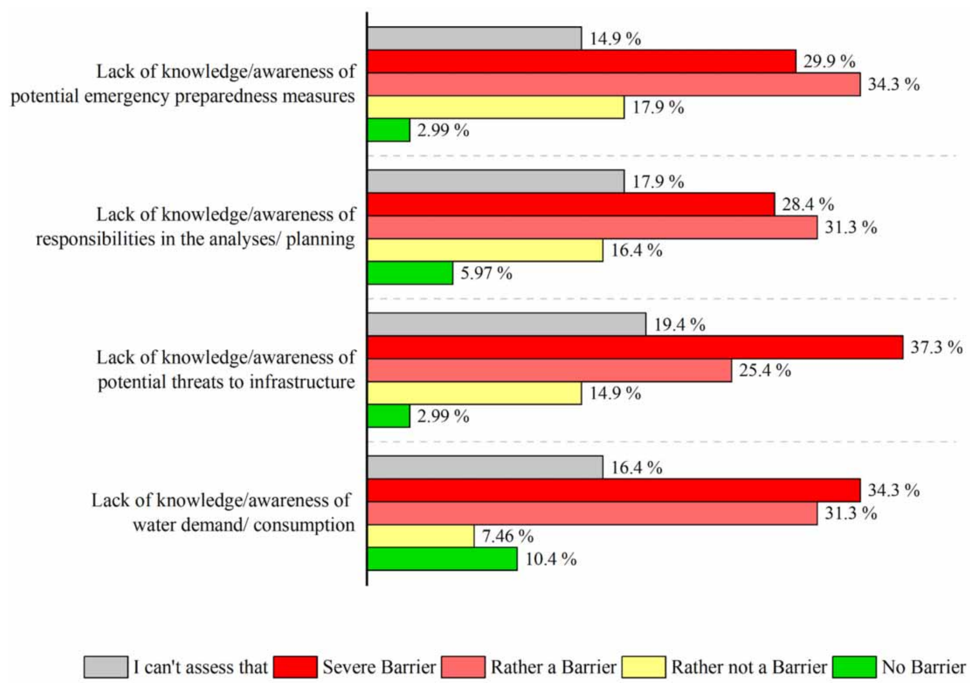


Figure 2 | Perceived role of awareness in emergency water supply preparedness planning in German healthcare facilities.

Interviewees stressed that there is not only a lack of awareness within the hospital but also among facility external actors. Two of the interviewees emphasized the need for the hospital to know which resources might be available for support. They found it equally important that external actors are aware of the hospital's emergency water supply needs, as the Head of the Department for Disaster Control at a fire brigade training school stated: '*the authority has the awareness that their actions with drinking water could have an impact on the hospital. […] The [city name] increased chlorination in 2013 during the floods, and as a result, they could no longer sterilize their surgical equipment, because the plant cannot tolerate so much chlorine. But that's not what the authority has on the radar either.*'

Awareness is seen as difficult to build without the memory of a recent disaster, such as the one in Ahr Valley in 2021, as one interviewee, who was a senior physician at a hospital, noted: '*So the Ahr Valley incident/ disaster was […] such a wake-up call […]. That's how we humans are: if something hasn't happened. One must be glad that the fire brigade is not abolished in a village if it has not burned in ten years. So always, when nothing happens for a certain period of time, people think 'oh that's not so bad.' And then we are suddenly surprised when something happens again.*'

Another barrier that was mentioned by the interviewees is the technical nature of the subject, which often neglects organizational aspects. These aspects include communication and collaboration measures. This was stressed by the Head of the Hygiene Department at a State Office of Health, who stated, '*So they've already thought about it, especially the technical departments […]. But in the end, when it comes to implementation, there are usually some small organizational aspects that get in the way.*'

Furthermore, the complexity of the legislation and the lack of knowledge of the probability of failure of the water supply system were seen as barriers by the interviewees. Overall, a significant proportion of the interviewees stressed the importance of creating awareness and becoming more sensitive to the topic, to overcome these barriers.

Emergency response plan and trainings

As the emergency response plan will include HIMT structures and a training concept will be provided, an assessment of the systems in use was conducted with a survey. The survey showed that 47% of hospitals use the recommended structures comparable to the Fire Service Standard 100, 24% use different, not further classified structures, 15% of hospitals use their standard organizational structures, and for 14% of the participants, the structures are unknown. This result is underlined by interviews where the recommended HICS was named to consume too many personnel resources, especially in smaller hospitals.

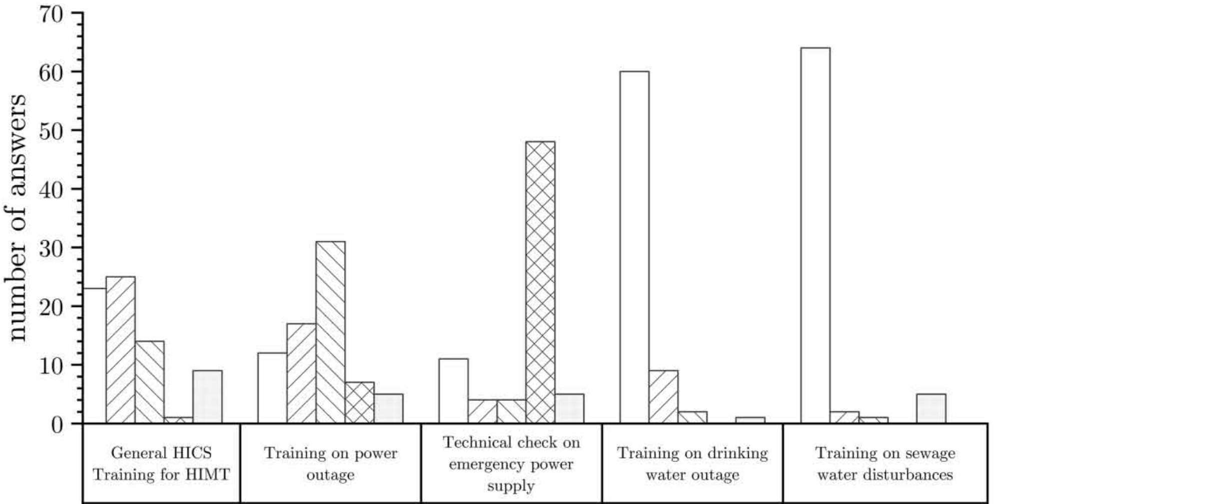
The survey included the frequency of trainings of HIMT in general and for specific infrastructure topics. The results are presented in Figure 3. It shows that of 72 hospitals, 23 do not conduct any general trainings for the HIMT, 25 conducted one training in the past 5 years, 14 train the HIMT annually, and 1 hospital conducts biannual training. Training on power outages and technical checks on the emergency power supply is however conducted more frequently in most hospitals. The regularity of technical checks on the emergency power supply (test run of fuel power generators) is predictable as they are mandated according to technical standards. Trainings on either drinking water impairments or sewage water disturbance is rarely performed in hospitals.

Event-specific method for risk assessment

RA consists of three steps: risk identification, risk analysis, and risk evaluation (EU 2016; ENISA 2023). It is a systematic process for understanding and evaluating risks and the central basis for adequate and targeted emergency preparedness planning. As shown in Figure 4, the RA methodology of the NOWATER project considers all aspects of the WSP, extends these approaches, adapts them to the field of application, and provides detailed descriptions of the assessment steps. One of the most important additions is the extension of the risk-based water network approach to hospital processes in accordance with HTM 04-01 of the Department of Health (Department of Health 2016, p. 26), to identify the risks to the functionality of a hospital and derive measures accordingly.

The assessment consists therefore of two main sections:

1. RA of hospital processes ('hospital functional unit (HFU)')
   Identification and evaluation of risks of a water supply impairment to a hospital's functionality under consideration of planned emergency measures. Identification of most critical and vulnerable hospital processes.
   In the NOWATER project, the wording 'hospital functional unit (HFU)' is used instead of hospital processes. This includes medical departments, devices, or supporting functions (e.g., IT).



	General HICS Training for HIMT	Training on power outage	Technical check on emergency power supply	Training on drinking water outage	Training on sewage water disturbances
Unknown	9	5	5	1	5
Biannual	1	7	48	0	0
Annual	14	31	4	2	1
Once in the last 5 years	25	17	4	9	2
Never	23	12	11	60	64

Figure 3 | Comparison of training concerning infrastructure in hospitals.

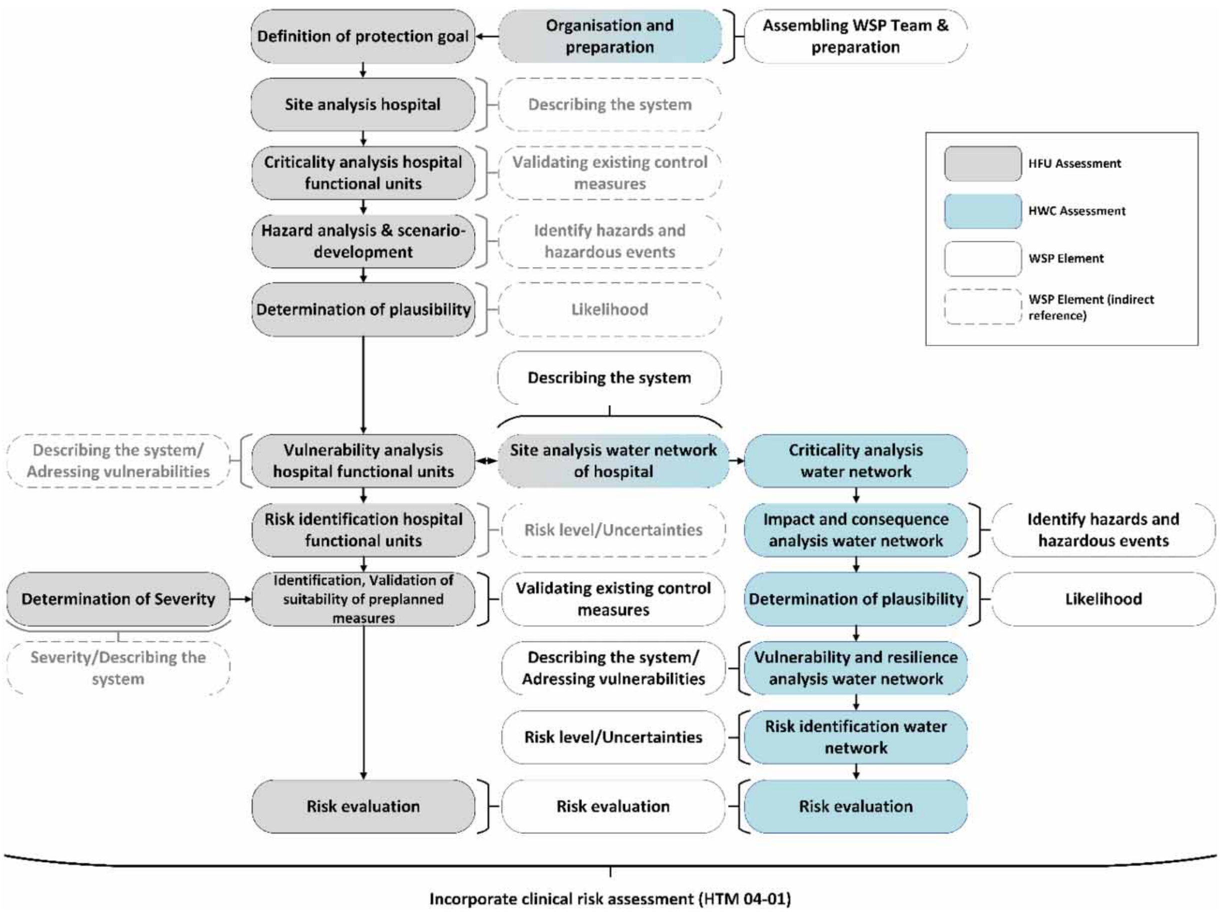


Figure 4 | NOWATER risk assessment methodology compared to the WSP approach.

2. RA of the water networks ('hospital water components (HWC)') based on the assessment of the hospital processes
   Detailed review of the hospital water networks to identify, analyze, and evaluate the risk of impairment to the respective network components. This allows the identification of areas of the network for technical hardening measures and where emergency supply should be applied.

The following five examples demonstrate essential differences between the NOWATER methodology and the WSP approach. A detailed description of processes and methodology including examples can be found in the publicly available project report (TIB 2023).

EXAMPLE I: PREPARATION AND RESPONSIBILITIES

Bringing competencies together is essential for the preparation and implementation of the RA. During the implementation in hospitals and healthcare facilities, the NOWATER project demonstrated that supplementing the specifications of the WSP with further required competencies is of central importance (Figure 5). These findings are based on experience in carrying out RA under real-life conditions, aligning with recommendations of the manual for hospital emergency planning of the German Federal Office of Civil Protection and Disaster Assistance. To combine these areas of expertise, the creation of an internal team with essential functional areas is necessary (Figure 5).

Within the framework of Integrated Risk Management (DIN 2019), external actors must also be involved. As hospitals are considered 'critical infrastructure,' the respective civil protection authorities, water supply companies, health authorities, and so on must be included within the coordination and conduction of emergency preparedness planning.

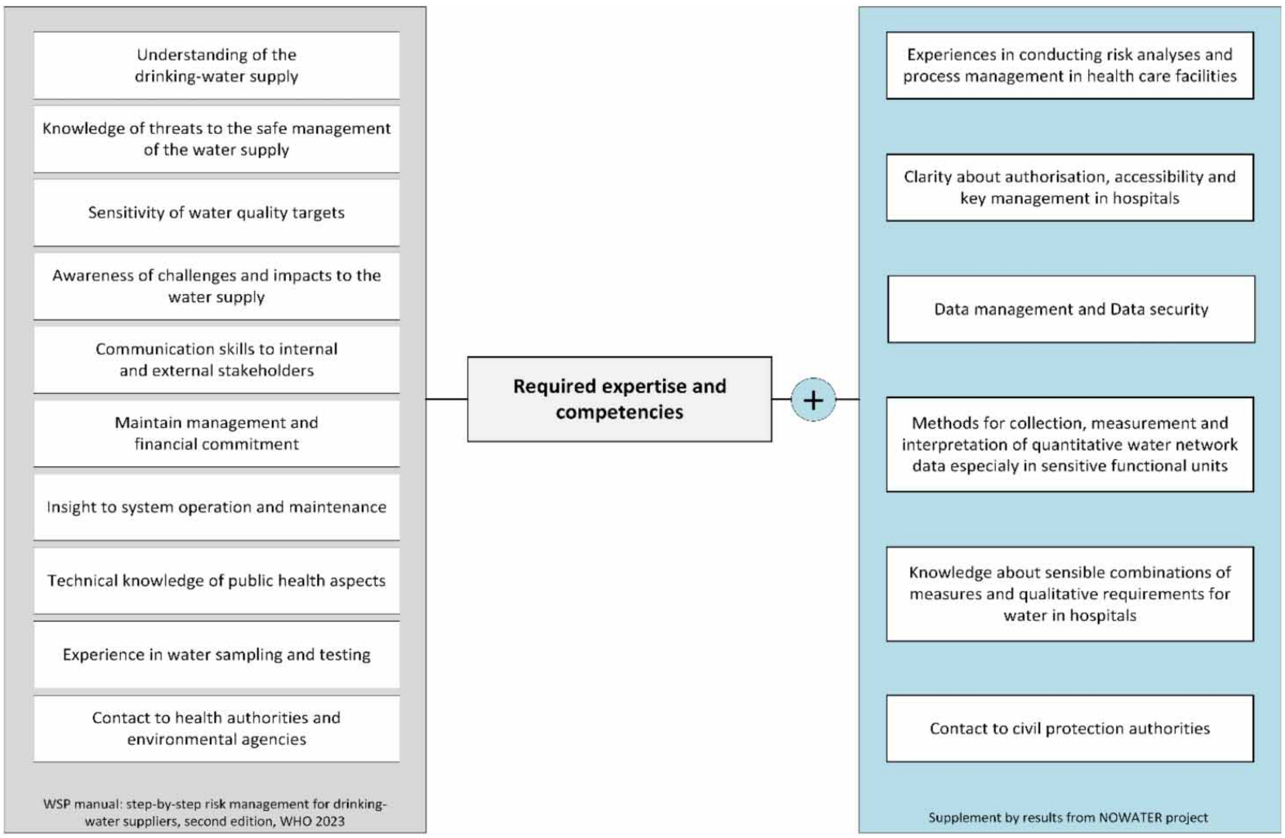


Figure 5 | Required expertise and competencies in the WSP team with supplement by results from NOWATER project.

EXAMPLE II: CRITICALITY ANALYSIS

The WSP Manual (WHO 2023) does not describe an approach for identifying essential processes, but merely points out their consideration. Therefore, two approaches will be described here to further articulate the needs as identified by the authors.

(i) Analysis of HFU

This analysis enables the scenario-independent identification of HFUs that are essential for the desired level of provision of service and prevention of negative effects.

The criticality of each HFU is assessed based on the following criteria:

- Quantity and quality (Q)

  'Quality' is a measure of the importance of the HFU for the desired level of provision of service and prevention of negative effects. 'Quantity' – as a damage parameter – indicates the extent of the impact of an HFU impairment. If it is assessed that an HFU impairment has no influence on the desired level of provision of service and prevention of negative effects, the quality is 0. Otherwise, the quality value is compared with a specially numerically defined 'capping value,' which is dependent on the desired level of provision of service or prevention of negative effects (e.g., percentage of service level or number of persons affected) (Federal Office of Civil Protection & Disaster Assistance (BBK) 2017, p. 43). Simplified example: The aim is to prevent fatalities caused by the failure of the HFU 'intensive care unit.' The immediate failure of an intensive care unit can endanger the lives of treated patients (quality). The capping value was set by the analysts at 40 affected patients. The intensive care unit in question has 20 beds. The quantity is therefore specified as 0.5 (50%).
- Redundancy (K)

  Assessment of the existence of suitable HFU redundancies or alternative modes of operation, which positively influence quality and quantity without negative effects.
- Maximum tolerable downtime (MTD)

  Identification of the time period at which HFU impairment or failure results in continuing and intolerable damage. These values are assigned to a qualitative category, which in turn corresponds to a unitless nominal value.
- Interconnectivity (I)

  As parameters for dependencies, the 'normalized harmonic closeness centrality' and the weighted degree of interconnectivity are determined and aggregated to an overall interconnectivity.
- Strength of knowledge (SoK)

  To assess potential uncertainties in conducting the analysis (Apostolakis 1990; Helton & Burmaster 1996), the strength of knowledge (adapted from (Aven 2017) and (Flage *et al.* 2014) is determined as a value between 0 and 1. The strength of knowledge is determined based on the parameters 'assessment of assumptions or simplifications made,' 'number and relevance/reliability of available data and information,' 'degree of agreement in the working group and/or among experts,' and 'assessment of the extent to which the phenomenon under consideration is generally understood and if accurate models exist.'

The lower the strength of knowledge, the higher the level of criticality.

The criticality (Cr) of an HFU is calculated according to (1) (roughly based on TZW (2014)) with a range of values [0;1].

$$\mathrm{Cr}_{\mathrm{HFU}}(i) = \left(\frac{\mathrm{MTD}(i) + I(i) + ((Q(i) \cdot (1 - K(i))) \cdot 1.5)}{3.5}\right)^{\mathrm{SoK}} \tag{1}$$

Side condition:

If $\mathrm{Cr}_{\mathrm{HFU}}(\mathrm{i}) > 1$, then $\mathrm{Cr}_{\mathrm{HFU}}(\mathrm{i}) = 1$

In addition, dependencies of other critical HFUs have to be considered by an iterative approach. The division by 3.5 is used for normalization to 5 classes from 'less critical' to 'very critical.' All 'critical' HFUs ($\mathrm{Cr}_{\mathrm{HFU}} > 0.7$) are further analyzed and evaluated using the vulnerability analysis. The applicability of the formula was tested in various hospitals, particularly in the western and southern parts of Germany.

(ii) Analysis of hospital water network

The purpose is to identify the HWCs relevant for supplying the critical HFUs considering specific water flows in HWC, average total flow in water network sections (Wang *et al.* 2019), redundancies, a time factor (TZW 2021), and the SoK as uncertainty factor.

EXAMPLE III: VULNERABILITY AND RESILIENCE ANALYSIS

Vulnerability is defined as 'a measure of the assumed susceptibility of an asset to adverse effects in relation to a specific event' (BBK 2010, p. 60). The WSP Manual addresses the identification and consideration of vulnerabilities (WHO 2023) but does not describe the methodological approach. Accordingly, two variants will be described here.

(i) Analysis of HFUs

The scenario-based vulnerability analysis is applied to all HFUs previously identified as 'critical' without the consideration of emergency preparedness planning.

Vulnerability per HFU is assessed based on the following criteria: 'exposition' (defined within the scenario development. From this, it is possible to deduce which functional units are directly or indirectly affected by the event), 'functional susceptibility' (possible impact of the scenario on the HFU; for this, the degree of dependence of the HFU on drinking water must be evaluated; considering dependencies between HFUs), 'substitutability/compensation' (examination of existing nonemergency water supply substitution and compensation measures), 'recovery time' (comparison of necessary time for implementation of compensation measures with MTD), and 'required water quality.'

(ii) Analysis of hospital water network

A scenario-based analysis regarding vulnerability and resilience factors is applied as the consequence of a scenario depending on the vulnerability and resilience of the HWC. The following factors were considered: exposition, functional susceptibility (linked to robustness and therefore to the identified potential negative consequences; the consequences are identified by an impact analysis using a fault tree analysis (Andrews & Ridley 2002)), robustness (the robustness is determined from the identified consequences by normalized characterization), recovery time, and uncertainty. Thus, conclusions concerning the effects of an assumed scenario on the HWC can be made. Vulnerability thus represents an indicator of the degree of negative consequences experienced during a hazard event (Thekdi & Aven 2021, p. 1291).

EXAMPLE IV: DETERMINING PLAUSIBILITY

The plausibility of a scenario considered replaces the 'likelihood' factor used in WSP, as this factor is subject to statistical and epistemic uncertainties (Darby 2009; Tchórzewska-Cieślak 2009). This could lead to a denial (Renn 2004) or ignoring of risks (Weber 2006).

(i) Analysis of HFU

Plausibility is calculated based on the variables 'reasoning by argumentation,' 'conviction by knowledge background,' and a statistically insignificant probability (Siebel 2003, pp. 265–266, Winko 2015, p. 508) using fuzzy logic to compensate for uncertainties (Grossi 2005, p. 34; Tchórzewska-Cieślak 2011, p. 146).

(ii) Analysis of hospital water network

The plausibility for identified negative effects of the selected scenarios on the HWC is calculated on the basis of a 'conditional plausibility' since the occurrence of a negative effect depends on the occurrence of a scenario (e.g., negative pressure in the event of a pipe rupture).

EXAMPLE V: RISK DETERMINATION AND EVALUATION

Different methods can be used for risk determination and evaluation. However, the variant of the risk matrix most commonly used (WHO 2023, p. 51) is not ideal due to incomplete information (Cox 2010, p. 123). To allow for more exact prioritizations, previously described factors are included in the NOWATER risk definition. Priority is then given not only according to the risk values (WHO 2023, p. 48) but also in particular based on criticality and vulnerability. These parameters indicate where it is possible and expedient to increase resilience through emergency preparedness measures.

Table 1 | Definition of risk levels

Risk level	Numerical risk value
Low risk	$R_{HFU} \leq 4.03$
Rather low risk	$4.03 < R_{HFU} \leq 6.042$
Moderate risk	$6.042 < R_{HFU} \leq 8.16$
High risk	$8.16 < R_{HFU} \leq 11.12$
Very high risk	$R_{HFU} > 11.12$

(i) Analysis of HFU

The basis of the risk definition developed here is the combination of probability of occurrence, consequences, and vulnerability (Rak 2009; AWWA *et al.* 2010). As the criticality metric already contains the potential consequences for hospital functionality and plausibility is chosen as the reference variable instead of the probability of occurrence, the NOWATER RA methodology utilizes the following risk definition (2):

$$R_{HFU} = \begin{cases} 0 \text{ if } V_{HFU} = 1 \\ V_{HFU} \cdot e^{Cr_{HFU}} \cdot P^{0,4}, \text{ else} \end{cases} \tag{2}$$

where V_{HFU} is the vulnerability of HFU, P_{HFU} is the plausibility of scenario, Cr_{HFU} is the criticality of HFU.

The applicability of the formula and following Table 1 were successfully tested in various hospitals, particularly in the western and southern parts of Germany.

The risk values are subjected to a risk comparison and the risk profiles are evaluated according to the most urgent need for measures (BBK 2008, p. 58). If the values are beyond the acceptable range, measures must be implemented.

(ii) Analysis of hospital water network

Risk is determined based on the definition in J100-10, as an aggregation of threat likelihood, consequence, and vulnerability (AWWA 2014, p. 4). Uncertainties are considered in the derivation of plausibility, consequences, vulnerability, and criticality, and are thus indirectly included in the process described here. Furthermore, the robustness and thus the potential extent of damage was integrated into the resilience and vulnerability analysis, which is why it has not been included separately.

Accordingly, the definition of risk adopted here is as followed (R_{HWC}):

$$R_{HWC} = \sqrt[3]{V_{HWC} \cdot P_{HWC} \cdot Cr} \tag{3}$$

where V_{HWC} is the vulnerability and resilience of HWC, P_{HWC} is the plausibility of scenario and effect on HWC, and Cr_{HWC} is the criticality of HWC.

The risk values obtained also need to be subjected to a risk comparison and evaluation. The aim of the risk comparison is to identify those network components with the highest risk and then an evaluation of the risk profiles according to the greatest need for action. A comparison with the HFU criticality values should also be included, as these provide additional prioritization functions.

Conversion to NOWATER toolset

To address limited time and human resources and to simplify application and comprehensiveness, the RA methodology was implemented in a Microsoft Excel-based toolset, which was developed according to aspects of a user-centered design and is currently being evaluated under real-world conditions.

Water demand database

During the water audit, water demand for different hospital areas and functional units depending on the drinking water supply was analyzed (Figure 6). This included drinking water for personal use (hygiene, toilets, drinking), as well as medical and technical devices.

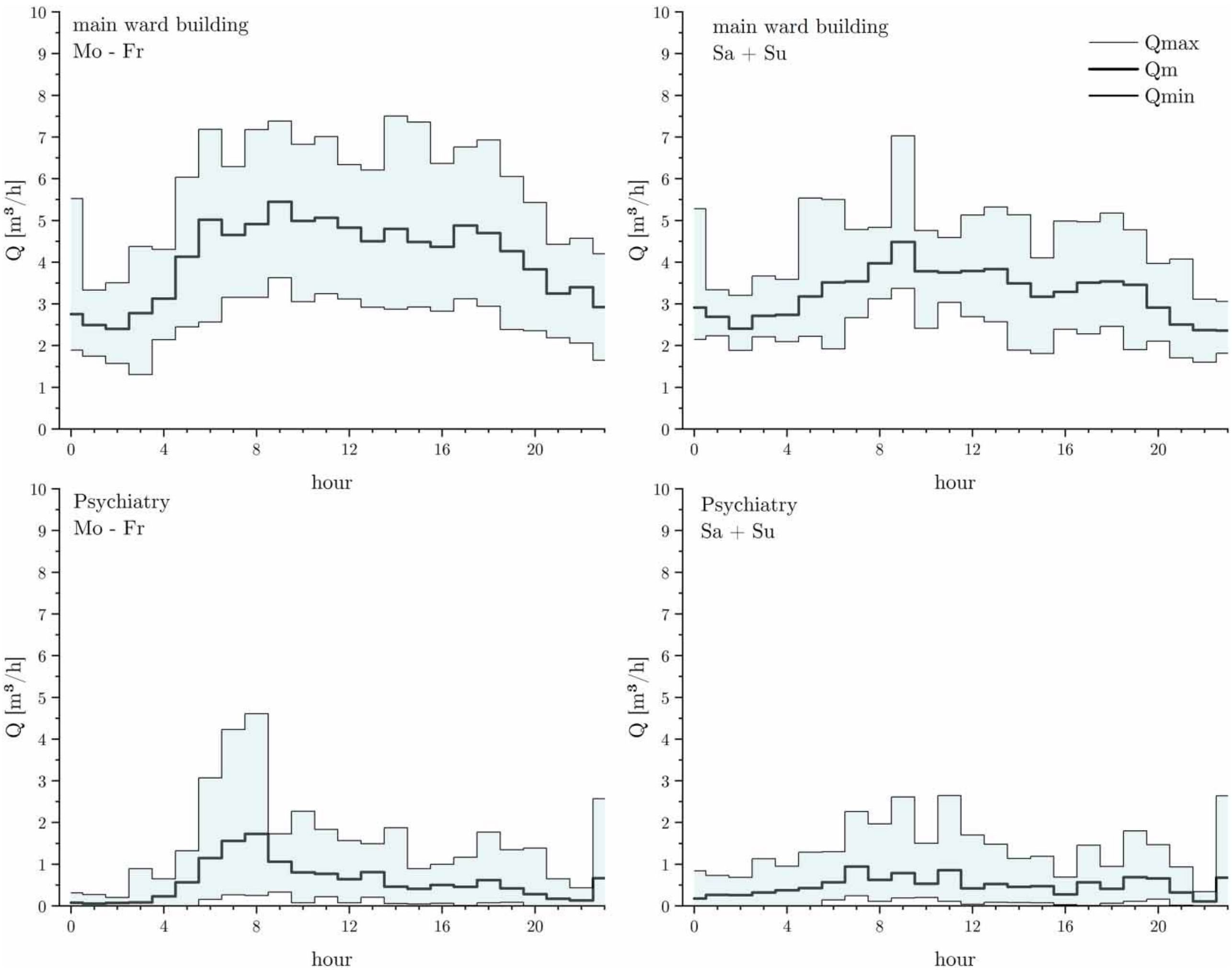


Figure 6 | Examples for water demand patterns for main ward building and psychiatry for weekdays and weekends.

The identification of relevant water consumers was a necessary part of the RA providing the basis for planning the measurement campaigns whose results are presented below. Technical devices that directly require drinking water include ventilation technology, reverse osmosis for laboratory needs, and cleaning and disinfection units. Medical devices directly requiring drinking water include the dialysis machine, magnetic resonance scanner, and medical laboratories. With regard to indirect dependencies (e.g., dependency of a unit on cleaning and disinfection units), there is a significantly higher number of dependencies.

Measurement results and characteristics of the different objects are shown in Table 2. In addition to the average daily demand, fluctuations, especially with peak demand, are important to determine the required volume of balancing and storage tanks. Therefore, the daily ($f_d = Q_{d,\max}/Q_{d,m}$) and hourly peak factors ($f_h = Q_{h,\max}/Q_{h,m}$) were determined from the measurements, where $Q_{d,\max}$ and $Q_{h,\max}$ are the maximum water demand per day and hour, respectively, and $Q_{d,m}$ and $Q_{h,m}$ are the respective average demands.

In Table 2, the daily water demand in m^3/(bed·day) is related to the number of beds (total capacity) and in m^3/(patient·day) related to the number of occupied beds, as both methods are used in the literature and technical standards such as DVGW W 410 (DVGW 2008). Water demand of the central disinfection and sterilisation (CDS) is related to the number of sterile units (STUs). One STU is defined as a container with the dimensions of $60 \times 30 \times 30\ cm^3$ and can contain a varying number of different materials to be disinfected.

Standard DVGW W410 (DVGW 2008) specifies the daily water demand with 0.13–1.2 m^3/(bed·day) and 0.12–0.83 m^3/(patient·bed·day) for water consumption per bed. The measured values for the ward-only houses are in the lower to

Table 2 | Results of water demand measurement campaigns

Object	Characteristics	Specific cold water demand[a]	Peak factor f_d	Peak factor f_h
Ward building with dialysis unit and emergency department	74 beds in medical wards Large outpatient department	1,007 L/(bed·day) 1,805 L/(patient bed·day)	1.4	2.2
(Main) ward building with intensive care unit and CDS	340 beds in medical wards 18 beds in intensive care unit CDS composed of 6 washer disinfectors, 1 cart washer, 2 steam sterilizers, 1 plasma sterilizer with an output of 30,000 sterilization units/year	257 L/(bed·day) 525 L/(patient bed·day)	1.1	1.6
Psychiatry	204 beds	64 L/(bed·day) 140 L/(patient bed·day)	1.2	4.9
Geriatrics	156 beds	153 L/(bed·day) 238 L/(patient bed·day)	1.3	1.7
Medical care center and private ward station	40 beds large outpatient department composed of 4 medical offices	356 L/(bed·day)[a] 498 L/(patient bed·day)[a]	1.8	3.0
CDS	6 washer disinfectors, 1 cart washer, 2 steam sterilizers, 1 plasma sterilizer with an output of 30,000 sterilization units/ year	482 L/STU[a] Softened water: 310 L/STU	1.3 1.4	2.2 2.4
Surgery	11 operating rooms, 6,800 surgeries/year	201 L/(surgery) 3 L/min (knife to skin time)	1.3	2.7
Dialysis unit	12 patients per day	712 L/(patient·day)	1.5	2.9

middle range of these values. Deviations from these values only occur in buildings that are not fully equipped with beds (e.g., due to outpatient medical areas), and the reference data therefore only represent a part of the building, which is more accurately compared to an office building. Here, also peak factor f_h with a value of 4.9 is significantly higher than in the other buildings. The other values agree relatively well with the peak values of $f_d = 1.3$ and $f_h = 3.2$ from DVGW W 410 (DVGW 2008).

The range of the measured values is noticeable. This is to be evaluated depending on the existing functional units, such as the CDS or dialysis, but also regarding the abilities and mobility of the patients (psychiatry or intensive care). The specific water demand in psychiatry is comparable to the typical domestic water demand in Germany of about 125 L/(cap·day). As the derivation of generally valid figures is difficult, the figures must be taken as an incentive to look at specific drinking water requirements in the individual clinics.

The level of the daily peak factor gives an indication of how synchronous the daily routine of patients with regards to water use transpires within a building. The higher the f_d, the more the patients follow the same routine. It should be noted that the measurements cover only 1 week at a time. Therefore, there may well be larger deviations from the values determined in the course of the year.

The measured values represent the regular operational water demand in the participating hospital.

In the event of an emergency, measures to reduce peak demand and provide a steady water supply or to reduce the total consumption to manage lower water availability are possible. Peak demand levels can be reduced, for example, by not using showers in buildings simultaneously. Overall demand can be reduced by outsourcing water-intensive areas such as the CDS or temporarily banning showers.

Options for an emergency water supply

The aim of the RA and the integrated analysis of water usage is to derive target-oriented measures where necessary. In practice, it has been shown that impairments of water supply cannot typically be managed by individual measures and require a more holistic response adapted to local conditions. The following resources could be used as possible measures to maintain water supply in an emergency: tanks to transport and store raw water and/or drinking water, disinfection devices, treatment units for particle removal prior to disinfection, booster pumps, and pipes to connect all units with each other and to feed treated water to existing installations. Based on the characteristics of the existing hospital infrastructure, the following technical components have been designed and manufactured.

For transportation and storage of raw and/or drinking water, two different tanks were designed: one tank with a net capacity of 1 m^3, mounted on a trailer that can be towed by a basic automobile, and one tank with a net capacity of 10 m^3, mounted on a hooklift frame. The capacity and design of both tanks were tailored to the vehicle equipment available to municipalities and emergency organizations.

Both tanks are equipped with a booster pump that can deliver the water at a pressure of approximately 2 bar. The 10 m^3 tank features a chlorine dioxide dosing and monitoring system for disinfection purposes. Both tanks are built in compliance with German Drinking Water Ordinance and technical rules (UBA 2022a) and thus certified for drinking water applications.

Tests confirmed that tank design and material selection do not increase bacterial regrowth potential and allow storage of drinking water without quality reduction for up to 7 days. Initial tank disinfection suffices before filling and disinfection during operations are unnecessary. Water disinfection in accordance with the Drinking Water Ordinance (BMG 2021) is however advisable for water storage exceeding 3 days at around 30 °C ambient air temperature.

To provide an efficient and reliable removal of particles from different types of raw water, ultrafiltration (UF) was chosen (Jacangelo *et al.* 2006). Recommendations for the design and operation of UF systems in municipal applications are provided by the DVGW standard W 213-5 (DVGW 2019). To produce a maximum amount of drinking water, a two-staged system was developed. Here, the second stage treats the backwash water from the first stage, resulting in a hydraulic yield of >99.9%. Long-term operation of UF systems typically requires the use of chemicals such as sodium hypochlorite and hydrochloric acid. The UF system tested in the NOWATER project was backwashed with air and water only. This reduces the need to stockpile dangerous chemicals that are prone to chemical degradation during long-term storage and requires safety and precautionary measures in storage and usage. The more efficient backwash allowed for a much longer filtration interval and higher flux compared to typical municipal applications. In combination with the high hydraulic yield, the specific production of treated water increased by 200%.

UF membranes have pores with a diameter in the range of 20 nm and retain particles including bacteria and viruses with an efficacy of up to 4 log (AWWA 2005). For the system described here, this has been demonstrated in pilot tests with groundwater, spring water, and surface water. However, smaller particles and dissolved substances are not retained. To extend the application of UF, dosing of powdered activated carbon to the raw water before the first stage was performed to allow for the removal of substances such as pesticides and organic industrial chemicals.

The UF system is mounted on a trailer that can be towed by a basic automobile. It can be equipped with one or two full-size UF modules (respective treatment capacity of 9 or 18 m^3/h). Turbidity of raw and treated water is monitored along with flow rates and transmembrane pressure, to ensure that the maximum permissible value of 0.2 NTU before the subsequent disinfection is not exceeded (UBA 2022b).

Raw water is fed to an internal storage tank equipped with a level sensor that can be switched off automatically if there is a lack of raw water. As soon as the fill level in the tank has reached the required level, the system restarts automatically. Therefore, an intermittent but still unattended operation is possible. The system can be commissioned in about 2 h. It is equipped with a remote-control system to monitor all relevant parameters and adjust operating settings.

Tanks and UF plant are complemented by a mobile service unit, also mounted on a trailer towable by a regular car. It is equipped with a protective filter, a water meter for volume proportional dosing of chlorine dioxide and an UV disinfection system. Depending on the circumstances of a specific emergency, the components can be used in various combinations (Figure 7).

DISCUSSION

Results have shown that social components of emergency preparedness and response in the field of water supply are often given insufficient attention in German healthcare facilities. Enhancing the overall preparedness and therefore the resilience of critical health infrastructures to impairments would require raising awareness on social as well as technical aspects. Survey and interview results show that actors are already aware of the necessity to integrate social and technical measures in water

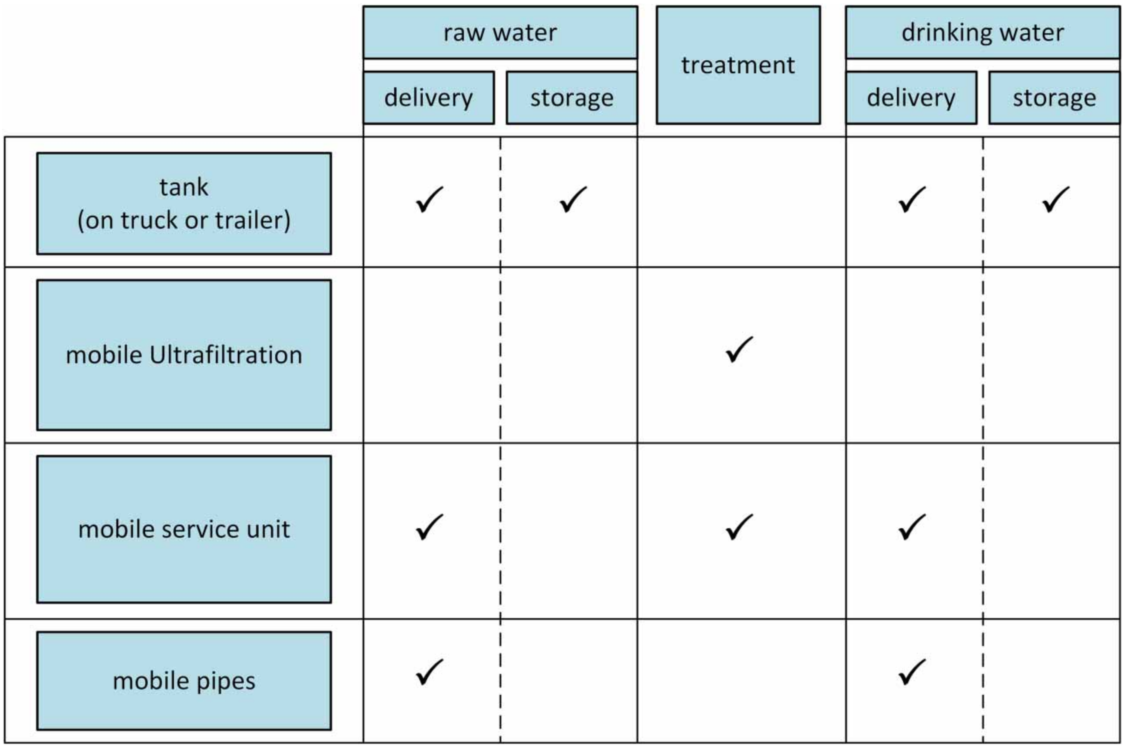


Figure 7 | Components for an emergency water supply and their combinability for different tasks.

safety planning, but the reality in hospitals is often different. A general lack of awareness about the vulnerability of healthcare facilities to water supply impairments was identified as one of the main barriers to taking action.

Paradoxically, high supply security and hence limited experience with supply impairment might be one of the underlying reasons for this gap. As a result, this raises the question of how to effectively build awareness of the need for water safety planning and the roles of different stakeholders including actors involved in healthcare but also crisis management as well as the public.

Ultimately, raising awareness could benefit social and technical aspects of water supply planning within the hospital by creating incentives to develop training and plans as well as prioritizing maintenance measures.

The results also lead to a possible need for an adaptation to HICS, including the needs of small hospitals. Furthermore, hospitals have shown a need for assistance with general training for the HIMTs, and more importantly instructions on drinking water impairment and sewage water disturbances.

To address the needs and constraints found in the interviews and surveys, different manuals for hospitals have been generated. This contains a model emergency response plan for HIMTs with adapted and scalable structures and with checklists and further assisting documents to implement and apply clear structures for incident management processes. The scalable structures for HIMTs can be used in different ways. Either small hospitals can choose a smaller HIMT to reduce the personnel resources needed or bigger hospitals can choose a smaller HIMT for smaller events. Therefore, a clear threshold for different levels of the HIMT needs to be determined by each facility according to the scale of an event. Especially for extreme events with severe effects on the drinking water supply, the establishment of HIMT structures is essential. Figure 8 shows the full HIMT, which can be adapted by reducing to Hospital Incident Commander and Sections S1–S4 (dark grey squares). Further reduction can be done by a combination of S1 with S4 and S2 with S3 and one staff for each combined section. All tasks of the cut sections then have to be transmitted to departments responsible for everyday business.

As a recommendation for the command process, a 10-point plan was generated and adapted as a synthesis from the American HICS Guidebook, more specifically the used Planning-P (Ballay 2014) and the German command process from the ICS

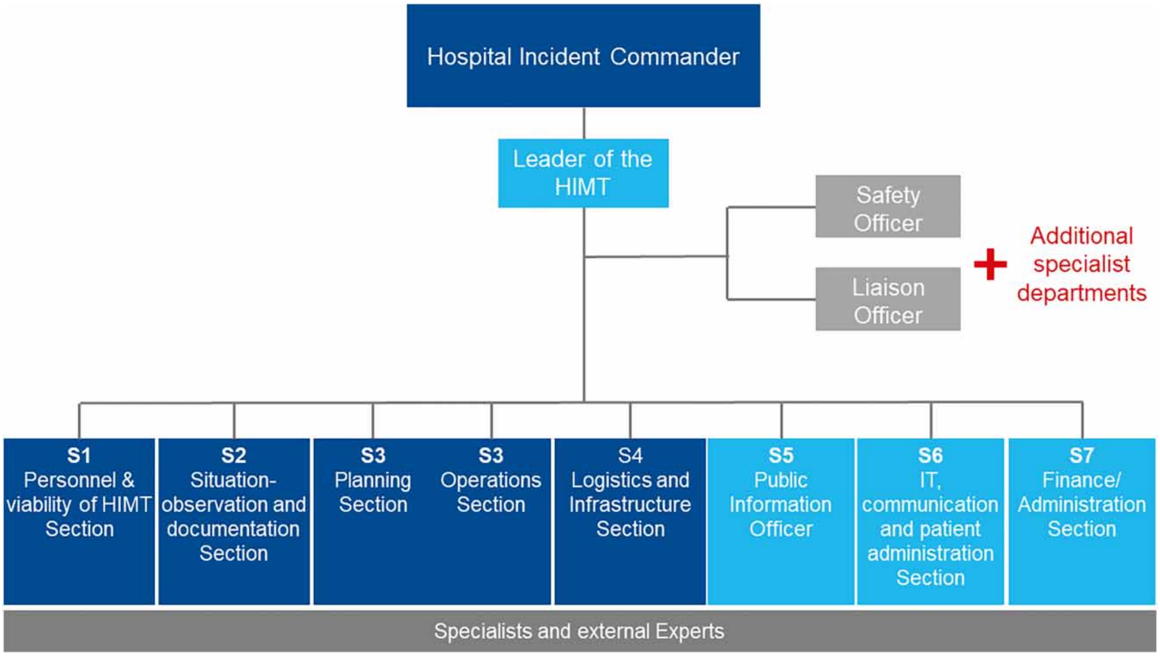


Figure 8 | Recommendation for a full-scale HIMT generated as a synthesis of the German ICS standard, the American HICS and the ISO 22320:2018.

standard (AFKzV 2007). The 10-point plan contains four consecutive steps at the beginning, which are carried out by a temporary, operational HIMT and then followed by six steps to be performed periodically:

1. Initial situation assessment using provided checklist
2. Launching initial measures of situation control
3. Evaluating the needs of the entire HIMT and sending an alarm
4. Briefing of HIMT
5. Detailed situation assessment
6. Determining strategic goals and evaluating the need for evacuation
7. Determining and prioritizing measures of situation control
8. Acting on the developed plan
9. Checking the success of measures
10. Restarting with step 5 or, in case of termination, launching recovery measures

To ensure HIMT can successfully work in incident management, a training manual was developed for scenario-based training in varying scales. Therefore, three types of training have been identified for use in hospitals. First, small-scale training is a scenario discussion to be executed either in different departments or within an entire HIMT. It is carried out as a moderated discussion guided by a chosen scenario and is used to raise awareness on the topic itself, and possible issues leading to further meetings to address identified needs. The second training is a tabletop exercise with the entire HIMT and can include external partners like emergency services or authorities. This training is conducted as management training guided by a chosen scenario intended to improve the management processes of the HIMT as well as technical skills according to the chosen scenario. The third option is a full-scale real-life training with the HIMT and all necessary resources and units onsite physically performing tasks. The training manual, therefore, offers five groups of scenarios varying from drinking water outages, shortages in electrical power, to sewage water disturbances and biological/ chemical contamination of the drinking water supply. Furthermore, each group of scenarios is scaled-up, e.g., one ward in the hospital is compromised to an entire city or region.

Risk assessment

The application of the NOWATER RA methodology in practice verified that the methodology is applicable and expedient. Results show that hospitals are highly dependent on water of drinking quality. This affects numerous hospital functional units that are essential for the overall functionality of hospitals, e.g., sterile supply, surgery, dialysis, or indirectly due to interdependencies between the functional units. This shows that cascading effects must also be considered to assess the impact of water supply restrictions. Furthermore, the scenario-specific analysis of consequences revealed that the impacts of a scenario not only affect the components of the water/wastewater networks themselves but also result in consequences from these impacts or the measures taken. For example, if chemical substances such as chlorine are used, these substances can damage the pipes and other components of the distribution system including reverse osmosis membranes needed for advanced treatment processes. In addition, it became apparent that if wastewater disposal is affected, significant restrictions on the use of drinking water are to be expected, as this is the only way to avoid overloads meaning backwater entering the building or environmental pollution.

To support one aim of the RA of deriving organizational and technical measures for an emergency water supply, the NOWATER project developed criteria on how to prioritize available combinations of options.

Water demand database

We recommend that operators of healthcare facilities carry out a water demand analysis in their facilities to determine the resources required for an emergency or replacement supply and to set up a contingency plan (CDC 2019). Data collected on water demand and peak factors within our project allow for a detailed estimation of water demand in other hospitals as they cover different uses, including pure ward buildings, ITC, and CDS units. Therefore, costly measurement campaigns such as those described here can generally be avoided. The magnitude of the peak factors is influenced by the simultaneity of water use in the respective areas, with higher simultaneity leading to increased peak factors. The time at which the peak demand occurs depends on the daily routine in the respective hospital. Such influences can be considered with little effort, e.g., by means of counting campaigns or key business figures.

If the data are to be transferred to other countries and regions of the world, differences in sanitation and medical equipment must be considered. However, the transferability may be limited, if uses such as cooling towers, kitchens, and laundries are taken into account. Here, reference data from other commercial areas should be used as an amendment.

Options for an emergency water supply

The effective use of technical components such as transport and storage tanks during emergency situations to balance water supply and demand requires knowledge of typical daily and hourly fluctuations in water demand. Despite their design for rapid deployment and minimal personnel usage, their technology necessitates a certain level of training for operation. To establish an effective deployment and maintenance system, collaboration between hospitals, municipalities, and emergency response organizations is essential. Optimal component placement locations must be determined, and responsibilities for maintenance and deployment must be assigned. To ensure appropriate utilization, preconditions for their application must be assessed and met as part of emergency preparedness planning, such as establishing a connection to the hospital's water supply, ensuring adequate access and space for component placement at the hospital, and ensuring access to electricity.

In cases where water disinfection is required, dechlorination may be necessary to protect hospital equipment that is susceptible to chlorine-induced damage.

CONCLUSIONS

It is crucial to create awareness about the importance of functioning water supply in hospitals and therefore emergency preparedness planning. However, the effectiveness of advanced approaches to enhance resilience and crisis management will depend on various factors. These include the awareness of responsible parties on such approaches and their incorporation in planning processes. To achieve this, it is essential to prioritize engagement with key actors, coordinate their interactions, and provide support throughout the planning process.

The risk of water impairments and the specifics of hospitals can be addressed in water safety planning using the RA methodology presented here. It extends the WHO WSP approach to provide added value for emergency preparedness planning, thus increasing the resilience of healthcare facilities. Publicly available data on water demand were supplemented by the authors but should be augmented by additional surveys by the operators of healthcare facilities. The installation of smart meters at appropriate locations is encouraged.

Emergency preparedness planning should be conducted as a mix of measures. This must include interaction of all internal and external stakeholders. All hospitals should take the precaution of determining what alternative water resources can be called upon in an emergency and what that process entails. One possibility of an emergency supply measure is the use of the technical components presented in this article. Their versatility allows for their use in various combinations and in a wide range of scenarios beyond just healthcare facility settings. Information on water quality collected in advance can improve planning reliability, especially for emergency water treatment and disinfection. The necessary technical requirements for the use of emergency water supply systems must be examined or created. Even though the equipment has been designed to be quickly commissioned and safely operated, regular training in its use must be scheduled.

Ultimately, this assessment confirmed that without a legal mandate including the assignment of responsibilities, as is the case with electricity supply, emergency planning for water supply will be insufficient and undertaken only voluntarily by few hospitals.

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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.

REFERENCES

AFKzV 2007 *Feuerwehr-Dienstvorschrift 100 (FwDV 100), Führung und Leitung im Einsatz, Führungssystem*. Board of Firefighting affairs, catastrophe protection and Civil Protection Leadership and Command in Emergency Operations. Command and Control System. German Regulation 100.

Andrews, J. D. & Ridley, L. M. 2002 Application of the cause–consequence diagram method to static systems. *Reliability Engineering & System Safety* **75** (1), 47–58.

Apostolakis, G. 1990 The concept of probability in safety assessments of technological systems. *Science (New York, N.Y.)* **250** (4986), 1359–1364. doi:10.1126/science.2255906.

Aven, T. 2017 Improving risk characterisations in practical situations by highlighting knowledge aspects, with applications to risk matrices. *Reliability Engineering & System Safety* **167**, 42–48.

AWWA 2005 *Microfiltration and Ultrafiltration Membranes for Drinking Water (M17)*. American Water Works Association, Denver.

AWWA (American Water Works Association, American Society of Mechanical Engineers, American National Standards Institute and Innovative Technologies Institute LLC) 2010 *J100-10 RAMCAP Standard for Risk and Resilience Management for Water and Wastewater Systems*. American Water Works Association, Denver.

AWWA 2014 *Risk Analysis and Management for Critical Asset Protection (RAMCAP) Standard for Risk and Resilience Management of Water and Wastewater Systems Using the ASME-ITI RAMCAP Plus Methodology: ANSI/AWWA J100-10 (R13)*. American Water Works Association, Denver.

Ballay, C. 2014 *Hospital Incident Command System Guidebook*, 5th edn. California Emergency Medical Services Authority, Sacramento, CA.

BBK 2008 *Federal Office of Civil Protection and Disaster (BBK) Schutz Kritischer Infrastruktur: Risikomanagement im Krankenhaus. Leitfaden zur Identifikation und Reduzierung von Ausfallrisiken in Kritischen Infrastrukturen des Gesundheitswesens. Critical Infrastructure Protection: Risk Assessment and Management in Hospitals. Guideline for Identifying and Reducing Failure Risks in Critical Healthcare Infrastructures*. Bonn.

BBK 2010 Federal office of civil protection and disaster (BBK): Methode für die Risikoanalyse im Bevölkerungsschutz. *Wissenschaftsforum* **8**, 60. Methods for risk assessment in civil protection.

BBK 2017 *Federal Office of Civil Protection and Disaster (BBK): Schutz Kritischer Infrastrukturen – Identifizierung in sieben Schritten: Arbeitshilfe für die Anwendung im Bevölkerungsschutz: Fachinformation. Critical Infrastructure Protection – Identification in Seven Steps: Working aid for use in Civil Protection: Technical Information*, 2017th edn. Federal Office of Civil Protection and Disaster, Bonn.

BMG 2021 Federal Ministry of Health (BMG) German Drinking Water Ordinance in the version published on March 10, 2016 (BGBl. I p. 459), as last amended by Article 1 of the Ordinance of September 22, 2021 (BGBl. I p. 4343).

Bross, L., Krause, S., Wannewitz, M., Stock, E., Sandholz, S. & Wienand, I. 2019 Insecure security: Emergency water supply and minimum standards in countries with a high supply reliability. *Water* **11** (4), 732.

Centers for Disease Control and Prevention and American Water Works Association 2019 *Emergency Water Supply Planning Guide for Hospitals and Healthcare Facilities*. U.S. Department of Health and Human Services, Atlanta. 2012. Updated 2019.

Cox, L. A. 2010 *Risk Analysis of Complex and Uncertain Systems*. Springer, New York, NY.

Darby, J. L. 2009 Tools for evaluating risk of terrorist acts using fuzzy sets and belief/plausibility. In: *NAFIPS 2009 - 2009 Annual Meeting of the North American Fuzzy Information Processing Society*, 14-17 June 2009, Cincinnati, OH.

Department of Health 2016 *Health Technical Memorandum 04-01: Safe Water in Healthcare Premises – Part B: Operational Management*.

DIN 2019 *DIN SPEC 91390:2019-12 Integriertes Risikomanagement für den Schutz der Bevölkerung*. Beuth-Verlag, Berlin. Integrated Risk Management in Civil Protection.

DIN EN 15975-1 2016 *Security of Drinking Water Supply – Guidelines for Risk and Crisis Management – Part 1: Crisis Management*. Beuth-Verlag, Berlin.

DVGW 2008 *Arbeitsblatt W 410 Wasser Wasserbedarf – Kennwerte und Einflussgrößen. German Technical Association for Gas and Water. Standard W 410 Water Demand – Characteristic Values – Influencing Variables*. DVGW, Wiesbaden.

DVGW 2019 *Technische Regel – Arbeitsblatt DVGW W 213-5 (A) April 2019 Filtrationsverfahren zur Partikelentfernung; Teil 5: Membranfiltration German Technical Association for Gas and Water. Standard W 213-5 Filtration Methods for Particle Removal; Part 5: Membrane Filtration*. DVGW, Wiesbaden.

European Commission (ed). 2016 *EU General Risk Assessment Methodology (Action 5 of Multi-Annual Action Plan for the Surveillance of Products in the EU (COM(2013)76) [Online]*. Available from: https://ec.europa.eu/docsroom/documents/17107/attachments/1/translations/en/renditions/pdf (accessed 28 April 2023).

European Commission 2020 *Directive (EU) 2020/2184 of the European Parliament and of the Council of 16 December 2020 on the Quality of Water Intended for Human Consumption*.

European Union Agency for Cybersecurity (ENISA) (ed). 2023 *Glossary: Risk Assessment [Online]*. Available from: https://www.enisa.europa.eu/topics/risk-management/current-risk/risk-management-inventory/glossary (accessed 28 April 2023).

Flage, R., Aven, T., Zio, E. & Baraldi, P. 2014 Concerns, challenges, and directions of development for the issue of representing uncertainty in risk assessment. *Risk Analysis: An Official Publication of the Society for Risk Analysis* **34** (7), 1196–1207.

Grossi, E. 2005 Medical concepts related to individual risk are better explained with 'plausibility' rather than 'probability'. *BMC Cardiovascular Disorders* **5**, 31–34.

Helton, J. C. & Burmaster, D. E. 1996 Guest editorial treatment of aleatory and epistemic uncertainty in performance assessments for complex systems. *Reliability Engineering & System Safety* **54** (2–3), 91–94. doi:10.1016/S0951-8320(96)00066-X.

Jacangelo, J. G., Patania Brown, N. L., Madac, A., Schwab, K., Huffmann, D., Amy, G., Mysore, C. H., Leparc, J. & Prescott, A. 2006 *Micro- and Ultrafiltration Performance Specifications Based on Microbial Removal*. American Water Works Association, Denver, Colorado.

Kowalzik, B., Hähn, F. & Helmerichs, J. 2020 *Handbuch Krankenhausalarm- und einsatzplanung (KAEP): Empfehlungen für die Praxis zur Erstellung eines individuellen Krankenhausalarm- und einsatzplans. Handbook Hospital Alarm and Emergency Planning. Recommendations for the Practice of Drawing up an Individual Hospital Alarm and Emergency Plan*, 2020 edn. Federal Office of Civil Protection and Disaster Assistance, Bonn.

Rak, J. R. 2009 Selected problems of water supply safety. *Environment Protection Engineering* **35** (2), 23–28.

Renn, O. 2004 Perception of risks. *The Geneva Papers on Risk and Insurance. Issues and Practice* **29** (1), 102–114.

Siebel, M. 2003 Plausibility, probability, coherence. In: *Proceedings der GAP.5. In Collaboration with Roland Bluhm and Chrsitian Nimtz. Fifth International Congress of the Society for Analytic Philosophy*, 22–26 September 2003, Bielefeld. Mentis Verlag GmbH, Paderborn, pp. 258–271.

Statistisches Bundesamt (Destatis) 2021 *Krankenhausverzeichnis. Verzeichnis der Krankenhäuser und Vorsorge- Oder Rehabilitationseinrichtungen in Deutschland, Stand 2019* (Hospital Directory. Directory of Hospitals and Preventive Care or Rehabilitation Facilities in Germany, as of 2019. Statistisches Bundesamt Wiesbaden). Wiesbaden.

Tchórzewska-Cieślak, B. 2009 Water supply system reliability management. *Environment Protection Engineering* **35** (2), 29–35.

Tchórzewska-Cieślak, B. 2011 Fuzzy failure risk analysis in drinking water technical system. *Reliability:Theory and Applications* **2** (1), 138–148.

Thekdi, S. A. & Aven, T. 2021 A risk-science approach to vulnerability classification. *Risk Analysis: An Official Publication of the Society for Risk Analysis* **41** (8), 1289–1303.

TIB 2023 Leibniz Information Centre for Science and Technology – University Library. Available from: https://www.tib.eu/en/search-discover/searching-in-the-tib-portal: funding code 13N15278

TZW (DVGW-Technologiezentrum Wasser) 2014 *Leitfaden zum Risikomanagement für Trinkwasserversorgungen hinsichtlich gezielter Einträge von chemischen, biologischen oder radioaktiven Substanzen Ergebnis des Verbundprojektes Schutz der Trinkwasserversorgung im Hinblick auf CBRN -Bedrohungsszenarien – STATuS -. Guideline on Risk Management for Drinking Water Supplies with Regard to Targeted Inputs of Chemical, Biological or Radioactive Substances Result of the Joint Project Protection of Drinking Water Supplies with Regard to CBRN Threat Scenarios – STATuS -.*

TZW (DVGW-Technologiezentrum Wasser) 2021 *Identifizierung Kritischer Infrastrukturen und Entwicklung Einer Methodik zur Räumlichen Kritikalitätsanalyse für die Leitungsgebundene Trinkwasserversorgung. Abschlussbericht Projekt KritisGIS-T. Identification of Critical Infrastructure and Development of a Methodology for Spatial Criticality Analysis for Piped Drinking Water Supply. Final Project Report KritisGIS-T.*

UBA 2022a German Environment Agency *Bewertungsgrundlage für Kunststoffe und andere organische Materialien im Kontakt mit Trinkwasser (KTW-BWGL).* Evaluation criteria document for plastics and other organic materials in contact with drinking.

UBA 2022b *German Environment Agency, List of Treatment Materials and Disinfection Processes According to § 11 of the German Drinking Water Ordinance*, 24th edn. Umweltbundesamt, Berlin.

van der Heijden, S., Cassivi, A., Mayer, A. & Sandholz, S. 2022 Water supply emergency preparedness and response in health care facilities: A systematic review on international evidence. *Frontiers in Public Health* **10**, 1035212.

Wang, F., Zheng, X., Li, N. & Shen, X. 2019 Systemic vulnerability assessment of urban water distribution networks considering failure scenario uncertainty. *International Journal of Critical Infrastructure Protection* **26**, 1–13.

Weber, E. U. 2006 Experience-based and description-based perceptions of long-term risk: Why global warming does not scare us (yet). *Climatic Change* **77** (1–2), 103–120.

Winko, S. 2015 *Zur Plausibilität als Beurteilungskriterium literaturwissenschaftlicher Inter-pretationen*. In: *Theorien, Methoden und Praktiken des Interpretierens* (Albrecht, A., Danneberg, L., Krämer, O. & Spoerhase, C., eds). de Gruyter, Berlin, Munich, Boston, pp. 483–511. On Plausibility as a Criterion for the Evaluation of Scientific Literary Interpretations.

World Health Organization (WHO) 2023 *Water Safety Plan Manual: Step-by-Step Risk Management for Drinking-Water Suppliers*, 2nd edn. World Health Organization, Geneva.

First received 29 April 2023; accepted in revised form 20 November 2023. Available online 5 December 2023