CHARLES UNIVERSITY

FACULTY OF SOCIAL SCIENCES

Institute of Political Studies

Department of Security Studies

Master's Thesis

2022 **Anna Fošumpaurová**

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Security Risks for Critical Infrastructure in the Water Management Sector

Master's thesis

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Year of the defence: 2022

Declaration

1. I hereby declare that I have compiled this thesis using the listed literature and resources only.
2. I hereby declare that my thesis has not been used to gain any other academic title.
3. I fully agree to my work being used for study and scientific purposes.

In Prague on 01. 05. 2022 Anna Fošumpaurová

References

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Abstract

The thesis examines the security concerns connected with the critical infrastructures in the water management sector, specifically hydraulic structures comprising the drinking water supply system. The thesis focuses on systemic risk and reliability assessment as a component of contemporary principles and security practices comprising the critical infrastructure protection (CIP) framework. The foremost objective is to explore to which extent Czech domestic procedures peruse the international expertise when assessing systemic risks stemming from the dependencies and interaction of water supply chain components. Investigating the present-state risk assessment relates strongly to the policy development at the European Union level. For that reason, the thesis commits particular attention to the Council Directive 2008/114/EC and Directive (EU) 2020/2184 and their impacts on the management and operation of critical infrastructures in the water supply sector. The thesis also studies the state-of-the-art reliability assessment methods for water distribution networks. The acquired knowledge is utilised to estimate the reliability of a study distribution network using stochastic simulation and survey selected network robustness-improving solutions. The thesis identifies the critical elements of a water supply system and delineates hazards to water infrastructure both of natural and anthropogenic origin. It concludes that while formal, structured risk and reliability assessment procedure is yet at the onset in the water supply sector, the Czech water management sector already harnesses international expertise, for example, in flood risk assessment, and contributes to its advancement at the European level.

Abstrakt

Diplomová práce se zabývá problematikou spojenou s bezpečnostní kritické infrastruktury v odvětví vodního hospodářství, a to zdravotně-inženýrskými objekty tvořící systém zásobování pitnou vodou. Práce je zaměřena na hodnocení rizika a spolehlivosti systémů, jež je součástí soudobých postupů ochrany kritické infrastruktury. Hlavním předmětem textu je prozkoumat, do jaké míry české tuzemské postupy vytěžují mezinárodní *state-of-the-art* metodické postupy zaměřené primárně na provázanost a interakci různých prvků vodohospodářské soustavy k zásobení pitnou vodou. Z tohoto důvodu je zvláštní pozornost věnována Směrnici rady 2008/114/ES a Směrnici Evropského parlamentu a Rady (EU) 2020/2184 a jejich dopadům na řízení a provoz těchto soustav. Práce se dále věnuje současným metodickým postupům hodnocení spolehlivosti rozvodných sítí spotřebišť pitné vody. Získané poznatky jsou aplikovány při řešení případové studie rozvodné sítě pomocí stochastické simulace a při porovnání zvolených variantních řešení k posílení robustnosti systému. Diplomová práce identifikuje kritické prvky soustavy k zásobení pitnou vodou a shrnuje naturogenní a antropogenní hrozby pro vodohospodářskou kritickou infrastrukturu. Práce shledává, že zatímco provádění strukturovaného, systematického a formalizovaného hodnocení rizika a spolehlivosti v oblasti zásobení pitnou vodou je teprve na počátku, české vodní hospodářství již využívá mezinárodní zkušenosti, například v oblasti hodnocení povodňových rizik, a přispívá k jejich rozvoji na evropské úrovni.

Keywords

Critical infrastructures, water management, risk analysis methods, interdependence, reliability

Klíčová slova

Kritická infrastruktura, vodní hospodářství, metody analýza rizika, vzájemná závislost, spolehlivost

Title

Security Risks for Critical Infrastructure in the Water Management Sector

Název práce

Bezpečnostní rizika pro kritickou infrastrukturu v oblasti vodního hospodářství

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List of abbreviations

ALARP	As Low as Reasonably Possible
ASCE	American Society of Civil Engineers
CBA	Cost-Benefit Analysis
CDF	Cumulative Distribution Function
CEN	European Committee for Standardization
CI	Critical Infrastructure
CIERA	Critical Infrastructure Elements Resilience Assessment
CINEA	European Climate, Infrastructure and Environment Executive Agency
CIP	Critical Infrastructure Protection
CISCPP	Critical Infrastructure Subject Crisis Preparedness Plan
CIWIN	Critical Infrastructure Warning Information Network
ČKAIT	Czech Chamber of Authorized Engineers and Technicians Active in Construction
COST	European Cooperation in Science and Technology
DDA	Demand-Driven Approach
DG ECHO	European Civil Protection and Humanitarian Aid Operations (European Commission)
DG ENER	Directorate-General for Energy (European Commission)
DG HOME	Directorate-General for Migration and Home Affairs (European Commission)
DG MOVE	Directorate-General for Mobility and Transport (European Commission)
DG SANTE	Directorate-General for Health and Food Safety (European Commission)
DG TREN	Directorate-General for Transport and Energy (European Commission)
E3PR	European Energy Efficiency Platform
EC	European Commission
ECI	European Critical Infrastructure
EIA	Environmental Impact Assessment
EISAC	European Infrastructure Simulation and Analysis Centre
ENISA	European Union Agency for Cybersecurity
ENTSO-E	European Network of Transmission System Operators for Electricity
EPA	Environmental Protection Agency (USA)

EPCIP	European Programme for Critical Infrastructure Protection
ERNCIP	European Reference Network for Critical Infrastructure Protection
EU	European Union
FAR	Fatal Accident Rate
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode, Effects, and Criticality Analysis
FR	Failure Rate
GRRASP	Geospatial Risk and Resilience Assessment Platform
HACCP	Hazard Analysis and Critical Control Points
HAZOP	Hazard and Operability Study
HSE	Health and Safety Executive
HSPD	Homeland Security Presidential Directive
IHIS CR	Institute of Health Information and Statistics of the Czech Republic
IMWM	Institute of Municipal Water Management
ISO	International Organization for Standardization
JRC	Joint Research Centre
KARS	Quantitative Analysis of Risk and Synergistic Effect
MTTF	Mean Time to Failure
NIPH	National Institute of Public Health
NPR	Node Pair Reliability
PCCIP	Presidential Commission for Critical Infrastructure Protection
PDD	Pressure-Driven Demand
PDF	Probability Density Function
PLL	Potential Loss of Life
PRI	Public Research Institution
SCADA	Supervisory Control and Data Acquisition
SCBA	Societal Cost-Benefit Analysis
SEA	Strategic Environmental Assessment
SOVAK	Water Supply and Sewerage Association of the Czech Republic
TA ČR	Technology Agency of the Czech Republic
TEU	Treaty of European Union
TGM WRI	T. G. Masaryk Water Research Institute

TNCEIP	Thematic Network on Critical Energy Infrastructure Protection
TTF	Time to Failure
TTR	Time to Repair
WDN	Water Distribution Network
WDS	Water Distribution System
WHO	World Health Organisation
WSP	Water Safety Plan
WTP	Water Treatment Plant

1 Introduction

The thesis focuses on contemporary issues concerning the risk and reliability assessment of hydraulic structures that comprise critical infrastructures (CI) and the related security concerns. The critical infrastructure in the water management sector functions to supply potable and non-potable water, preserve and manage surface- and groundwater resources, and operate the wastewater system. The undisrupted provision of the hydraulic structures' functions is vital to the performance of other sectors, including other CI. Water CI is a complex, highly interconnected system. For this reason, disruption or degradation of its components can result in cascade failures with severe negative impacts.

Hydraulic structures and their surroundings are dynamic systems. Their reliability is affected by natural, direct and indirect anthropogenic influences, imposed functional requirements, and social and economic developments. For that reason, the decision-making in water management handling the reliability and security of CI elements requires long-term prognoses and development concepts along with regular planning and operational management. Adverse deviations of future realities from planning and future provisions may subsequently precipitate the functional failure of hydraulic structures.

Specifically, the thesis focuses on the CI comprising the drinking water supply system, a set of utilities and facilities for providing water with sufficient pressure and flow rate to any user. Its reliable, consistent operation is indispensable for economic progress, public health, and social well-being. Within the established sub-field, the thesis surveys the current methods of risk assessment of water supply infrastructure in the Czech Republic and the research progress on the reliability assessment of water distribution networks.

A general water supply system consists of the following sub-processes: source of water and abstraction, conveying raw water for treatment, treatment of water following customer requirements, and transfer of treated water to the customer's distribution system. The components involved in the functioning of this process are linked in extensive geographical aggregation, similarly to other critical infrastructures, such as power grids and transportation networks. The system comprises intake facilities, pumping stations, water treatment facilities, water tanks, transmission mains and delivery conduits, and pipelines. Furthermore, the water treatment involves physical, chemical or biological sub-processes to remove impurities from raw water and modify its unsuitable properties.

The issues connected with cost-optimal design and operation of water distribution networks have drawn significant attention over the last two decades (Jung and Kim, 2018). Additionally, connecting mechanical and topological reliability considerations with hydraulic reliability for the distribution system is an objective that is currently gaining traction among scholars and in practice (Jensen and Jerez, 2018) (though one needs to recognise that the reliability-cost relationship has been regarded in usual practice at least implicitly). Although the term "*reliability*" of a water distribution network has no generally accepted definition, it denotes the ability of a network to provide water to meet the users' demand in quality and quantity, both within normal operating limits and in extraordinary situations. The qualitative indicators for treated water are consumer-specific and subject to relevant regulations and standards.

In simplified terms, the components of a water distribution network and the anterior elements of the water supply chain (water source, treatment facility, or transmission mains) determine its probability. The reliability of each component is then a result of its design, along with its technological and operational features. For this reason, the reliability considerations of the water distribution network have to pay close attention to several complexities affecting the level of service provided to users, including, e. g., components' faults, variability of demand, and the uncertainties in the capacity of pipes.

The water distribution networks are vulnerable to frequent failures and disruptions (per year). The interconnectivity of various components and interactions among them may negatively impact the global reliability function of the supply system. The operation and design of a distribution system must consider numerous hazards, both natural and anthropogenic. Adverse events may harm the system along the supply chain in different ways; their consequences are naturally categorised as quantity- and quality-related. From the perspective of risk management, failure of any component in the CI network, if not backed up by redundancies, may ensue in the consumer's water supply disruption. In the event of threatened water system reliability, the issue is more complicated owing to the potential transport of contaminants, the feasibility of identifying the source of contamination, and the timely response by providing alternative resources.

Moreover, because of uncertainty associated with data on the design of technologies and facilities construction details, the managers of water supply infrastructures carry out ordinary maintenance and regular safety inspections to ensure their continued security and operational sustainability. The manager should further develop plans for emergency preparedness and conduct a risk assessment under the relevant legal provisions. Risk-based safety management is an involved, multi-disciplinary process necessitating thorough research to identify and analyse the risk, as we the formal treatment of uncertainties. The standards regulating public health protection are increasingly rigorous with respect to the continuously deteriorating water quality. Additionally, the variance in the yields of water volumes further underscores the issues surrounding the evaluation of resources in terms of their reliability. Aside from the long-term natural developments (e. g., hydrological drought), it is also imperative to account for low probability events in the analysis, such as high concentrations of pollutants caused by water source contamination, treatment process failure, or various interferences with a distribution network.

Even though critical water structures are in the Czech Republic managed by state enterprises or joint-stock companies with the dominant state's share, there is no clearly defined process for identifying and evaluating human-driven factors and systemic risk emanating from synergistic or cascading effects. The Czech technical standards and Eurocodes apply well to (deterministic) common loading states, albeit less suited for emergencies with a low probability of occurrence and high impact. In the Czech Republic, the necessity to enhance the robustness and protection of CI components has been recognised in different security-strategic documents and legislation. Moreover, recent incidents worldwide underscore the issue of water systems reliability. In the Czech Republic, noteworthy events include the 2015 contamination of the drinking water supply in Prague or recurrent (since 2015) unsatisfactory drinking water quality in Trnová u Prahy caused by inadequate management of the treatment facility.

1.1 Research questions and methodology

The thesis peruses the Critical Infrastructure Protection (CIP) framework and its current principles to review the development of the European policy concerning the protection of vital systems (Dunn-Cavelty and Suter, 2012; Collier and Lakoff, 2020). The establishment of the European Union's role in the CIP (and the assurance of water supply quality) is significant for the advancements in the Czech protection policy.

The thesis further engages risk assessment as a constituent of contemporary security practices closely connected with CIP. The text works with the systemic reliability concept, drawn from the civil engineering field (Wagner et al., 1988; Votruba et al., 1993; Ditlevsen and Madsen, 2007), which may, for example, be conducive to the identification of critical assets and robustness-enhancing schemes. Reliability is a "*characteristic of the ability of a component or a system to perform a specific function*" (Aven, 1992, p. 5); it is measured in different ways (e.

g., average life, frequency of failure, or the probability that a component/ system is functional at a given time instance). Risk refers to the "*danger that undesirable events represents to human beings, the environment and economic values*" (Ibid., p. 6); it is quantified as a combination of the probability of occurrence of an adverse event and corresponding potential damage (ISO 31010). Reliability and risk contribute to safety management. Safety is the property of a component/ system not to endanger human health or the environment when performing a prescribed function for a specified time and under specified conditions. Safety management refers to the systematic process of taking necessary steps to achieve and maintain a safety level according to the acceptance criteria and objectives (Aven, 1992).

The thesis explores the extent to which Czech domestic procedures harness international expertise, e. g. when assessing the risks emanating from the interdependencies among components of the water supply chain. The research target of the thesis would also consider the contemporary security risks and vulnerabilities affecting the reliability of CI in water management. From the methodological standpoint, the secondary emphasis of the work would be the research of state-of-the-art reliability assessment of water distribution networks. The latter part would involve applying the tools of stochastic system simulation for modelling random failures in the water distribution network. The simulation would test selected robustness-enhancing options.

One would hypothesise that the previous experiences exposed vulnerabilities of the delimited critical infrastructure sector and, therefore, measures need to be taken to strengthen their robustness, especially in the cyber security framework or against terrorism. Secondly, one would propose that in the Czech context, current simulation-based methods are applied rarely for systemic assessment. The proliferation of simulation methods in practice may be relatively recent since their application requires adequate computing power. There may be a greater reliance on analytical techniques and deterministic risk assessment methods; these methods offer a solution to reliability and risk-related questions using more straightforward algorithms. Lastly, risk assessment in the water supply sector is yet in its beginning stages, and its application may be inconsistent depending on the service provider.

The research questions are following:

I. What are the current state-of-the-art methods for risk and reliability analysis of critical infrastructure in water management?
II. For which types of hazards can a state of emergency be reasonably expected to be declared?

The question of the practical application of reliability assessment of water distribution network is:

III. How reliable is the studied water distribution network and what measures can be taken to enhance its robustness?

Studying the current-state methods of risk assessment in the Czech Republic within the water supply infrastructures context relates strongly to the policy development at the EU level, specifically from the obligations stemming from the transposition of Council Directive 2008/114/EC and Directive (EU) 2020/2184. The thesis, therefore, focuses on the officially recommended methodologies adapted by the Czech water management sector.

The case study would select the simulation of stochastic systems for probabilistic reliability assessment (Zio, 2013; Brandimarte, 2014). The work applies Monte Carlo simulation with the EPANET 2.0 software widely used for the hydraulic analysis of distribution networks. The objective would be to simulate mechanical and hydraulic failures in a simple study network (a uniform experiment with assigned parameters) and obtain relevant reliability indices. The information necessary for the mechanical reliability assessment of the system or its components would comprise, e. g., the system failure mode configuration, the probability density function of each component's time to failure, time to repair and their parameters, and the mission time. The stochastic simulation has been utilised across different application areas to assess the reliability of equipment and plants (Manno et al., 2012). The merit of the simulation approach resides in the potential to investigate the real-world processes in a variety of scenarios that would otherwise be difficult or impossible to approximate analytically.

Aside from the data drawn from relevant literature, several specific data are necessary for reliability analysis. Generally, these may be summarised into technical (how the system is required to function), operational (how components/sub-systems operate and interact), reliability (e. g., estimations of failure rates, times to failure). Since manufacturer data are classified for natural reasons, the thesis would test the reliability model using technical standards, generic data issued by neutral organisations, and expert judgement data published as handbooks. These component reliability data sources are subjected to qualitative ranking (maintained, e. g., by European Cooperation for Space Standardisation). The elicitation of expert judgement is a complex process. It was in-depth examined (Ayyub, 2001; Meyer and Booker, 2001). Nevertheless, expert estimates may be essential for assessing extreme disruptive events with a very low probability of occurrence (Barker and Heimes, 2009; Ghil et al., 2011) as the relevant data may be missing.

1.2 Literature review

1.2.1 Risk and reliability assessment

The key theoretical text for the thesis would be "*Reliability of Water Management Schemes*" (Votruba et al., 1993). This work studies reliability issues specifically within water management and civil engineering context. The publication comprehensively addresses the issues of the reliability of water management planning, hydraulic structures and systems, acknowledging all their aspects, from water resources in nature to consumers. The thesis would also draw on "*Introduction to Dam Risk Analysis*" (Říha et al., 2008) and "*Reliability-Based Optimal Design of Water Distribution Networks*," a study by (Xu and Goulter, 1999). A paper by (Gheisi, Forsyth and Naser, 2016) would be a reference resource for literature in the context of methods of distribution network reliability, their organisation and classification.

The general research into water abstraction, water treatment technologies, water accumulation and distribution would be informed by (Tesařík et al., 1987). The text reviews the vast majority of presently used technologies. Further works by (Parsons and Jefferson, 2006; Crittenden et al., 2012) cover the recent theory and practice of water treatment system design and alternative treatment methods. (Tesařík et al., 1987) also outlines the basic principles for hydraulic calculations of distribution networks and is thus beneficial for the case study. A guide for calculating mechanical reliability is the publication by (Xing, Levitin and Wang, 2019). The security risks to critical infrastructure in water management were in detail investigated in (Haimes, 1998; Janke, Tryby and Clark, 2013; Clark and Hakim, 2014). Specific issues in relation to adverse human action are reviewed in "*Water Critical Infrastructure Security and Its Dependencies*" (Birkett, 2017). Various risk management approaches in water management sectors were studied in work by (Pollard et al., 2004).

1.2.2 State of the art in Security Studies

The current inquiries into critical infrastructure protection in security studies confront, aside from safety risks, mainly various issues pertaining to the broader subject of security governance (e. g., Heinimann and Hatfield, 2017). Notable scientific contributions include research by Dunn-Cavelty et al., for example, "*Securing 'the Homeland': Critical Infrastructure, Risk and (In) Security*" (Dunn-Cavelty and Søby, 2020). This text investigates the evolution of socio-political discourses surrounding CI protection, particularly from the constructivist and risk society perspectives. Authors pay close attention to the historical continuities in CI protection practices, threat perception/ construction and implementation of broad homeland security practices to compensate for vulnerabilities affecting modern, interconnected societies. A related study by (Dunn-Cavelty and Suter, 2012) examines governmental protection policies from different countries and strategies for the uninterrupted operation of critical information infrastructure. The contribution assesses how the goals overlap with assigned policies and whom these policies identify as the principal threat in the cyber domain. Another of the currently investigated topics focuses on the governance of CIs and the notion of public-private partnership (PPP). Its various aspects have been reviewed comprehensively, for example, in (Cui et al., 2018). Public-private partnership envisaged as a governance model for critical infrastructures was proposed by (Dunn-Cavelty and Suter, 2009) based on a network approach toward governance. The exacerbation of potential weaknesses of CI connected with PPP was outlined in (Giacomello, 2021).

The text (Dunn-Cavelty and Søby, 2020) also analyses different preparedness practices (also in McConnell and Drennan, 2007), namely the tools concerning building resilient CI to account for unpredictable and difficult-to-prevent hazards (e. g., the terrorist attacks). Accounting for unanticipated events would be currently relevant since Czech (and other countries') technical standards and methodological guidelines concerning constructions' technical properties and protection commonly operate with pre-defined stress situations in terms of safety factors (e. g., in the context of structural safety; Říha et al., 2008). The concept of resilience has been accepted relatively recently in security studies to mirror broader policy and social science developments (Petersen, 2011; Chandler, 2014; Brassett and Vaughan-Williams, 2015; Rehak, Senovsky and Slivkova, 2018a). Resilience was conceived by C. S. Holling and described as an inherent property of an ecosystem (Holling, 1973; resilience in dynamic systems theory was detailed in (Folke et al., 2010)). The resilience of anthropogenic systems (e. g., critical infrastructures) is a complex characteristic perceived as desirable target status (to be developed artificially). According to (Rehak et al., 2019), resilience is a system characteristic that decreases the system vulnerability and increases the capability to absorb negative aftereffects of disruptions, responsiveness and recovery, and adaptability to harmful events confronted before. The resilience approach refers to the intrinsic preparedness to maintain critical assets and services functional when adversely affected by external and or internal disruptive events. The resilience paradigm is a crucial component of the recently published amendment proposal of the European Critical Infrastructure Directive 2008/114/EC.

Numerous scholars have scrutinised critical infrastructure protection and resilience- and adaptation-based policies within critical security studies, studying these approaches towards CI protection within the neoliberal security paradigm, e. g. (Lundborg and Vaughan-Williams, 2011; Duffield, 2012; Dunn-Cavelty, Kaufmann and Søby, 2015), to mention a few. The article by (Coaffee and Fussey, 2015) proposes a concept of "*security-driven resilience*" to assess the multi-dimensionality of resilience policies. The work builds on narratives such as new localism, state-rescaling, human security, or the revolution in military affairs hypothesis. As such, "*security-driven resilience*" attempts to describe the resilience as comprising various national policies and guidelines whilst decentralising the power to the local spectrum, thereby derogating from the state-level security logic. A work by (Anderson and Adey, 2011) investigates the inclusive understanding of the emergency necessitated by governmental policies oriented on continuous preparedness, scenario-planning, and pre-emption. The authors illustrate such a notion in the 2004 UK Civil Contingencies Act. Other authors focused on the biopolitics perspective and the broader Foucauldian critique of "*resilience governance*" within the logic of governmentality (e. g., Aradau, 2010; Lundborg and Vaughan-Williams, 2011; Duffield, 2012; Reid, 2013; Collier and Lakoff, 2020). To illustrate, as Schmidt argues, resilience governance is related to a "*technology that is imagined to equip the subject to deal with uncertainty in 'general' rather than with 'particular' threats*" (Schmidt, 2014, p. 403).

It is noteworthy that the EU's policy-making has recently been integrating resilience-based strategies into several safety-critical domains and crisis management; their preparation was prompted to factor in a broader regional context and transboundary threats (Rhinard, 2019). Consistent with (Dunn-Cavelty and Søby, 2020), the EU's initiative in coordinating efforts toward enhancing CI protection may be traced to 2004 and possibly associated with the large-scale terrorist attacks of that period (Lindström and Olsson, 2009). EU's main framework is the European Programme for Critical Infrastructure Protection (EPCIP) and its legal tool, Council Directive 2008/114/EC. These instruments allow the designation of European Critical Infrastructure (ECI) in the transportation and energy sector or endorse joint contingency planning between neighbouring member states. The EU has also established less formal agencies, such as the Commission of a Critical Infrastructure Warning Information Network (CIWIN) or the European Reference Network for Critical Infrastructure Protection (ERNCIP), serving as platforms for discussion of good practices, tested procedures and expertise, and inclusion of a broader spectrum of stakeholders. As (Pursiainen, 2018) argues, the "*all-hazard approach*" to resilience in CIP is distinguishable after the 2012 review of EPCIP. The articles by (Boin et al. 2014; Van Asselt, Vos and Wildhaber et al., 2015) elaborate on the emergence of the EU's risk governance structures, specifically on the role of science and expert agencies in harmonising the security practices in the potentially politicised sphere of CI protection and concerns over the confidentiality of CI operational data. The contributions by (de Bruijne and van Eeten, 2007; Glorioso and Servida, 2012; Bossong, 2014; Cedergren et al., 2018) further analyse the EU's meta-governance efforts concerning the CI protection, taking on various sectoral and political differences, as well as different institutional practices. After the 2013 revision of the CI protection strategy, the EU aims primarily at protecting systems such as Eurocontrol, Galileo, the power grid and the gas distribution network (Boin et al. 2014). Therefore, a unified European approach toward CI protection has not been realised yet (Pursiainen, 2018).

1.2.3 Outline

The thesis is organised in the following way. The first part outlines the developments in and the contemporary tenets of the Critical Infrastructure Protection framework. The second part studies the establishment of the European risk management and CIP governance. This part is followed by the current state of protecting critical infrastructures in the Czech Republic. The third part looks specifically into the issues of the water supply CI sector on the European and Czech policy level, safety assessment of hydraulic structures, and the risk analytical tool developed and applied for water supply systems. The fourth part reviews systemic hazards to critical infrastructures in water management. The last part investigates the state-of-the-art reliability methods used to analyse water distribution networks and applies these insights in a case study to compare selected robustness-improving options.

2 Principles of the critical infrastructure protection

The contemporary understanding of critical infrastructure protection (CIP) has been cultivated since the mid-1990s. According to (Collier and Lakoff, 2020), the first official statement of the core principles of CIP, i. e. measures to assure the undisrupted, reliable functioning of CI, stems from the 1996 establishment of the U. S. President's Commission on Critical Infrastructure Protection (PCCIP) and its 1997 Report. While PCCIP did not yet identify any acute hazards (within its cyber-oriented scope), it referred to the potential vulnerabilities inherent to the interconnected infrastructures and outlined the steps to prepare the U. S. for future developments.

The 1997 PCCIP report led to the publication of Presidential Decision Directive No. 63, which elevated the protection of CI from physical and cyber threats to a national priority. The 9/11 attacks (and, e. g., 2003 wide-area blackouts in the Northeast of the U. S. and Canada) accelerated the efforts to constituting the CIP – the 2001 Patriot Act codified the legal definition of critical infrastructure: CI are "*systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, of any combination of those matters*" (United States of America, 2001, Section 1016). In other words, it stated that the advanced economies became vulnerable owing to the efficiency-oriented, networked energy and resource flows, industrial production processes, and information technologies (Harašta, 2018; Collier and Lakoff, 2020). This trend resulted in a tight coupling of social and economic systems that may translate into insufficient redundant capacity ("*CI congestion*") and propagate the risk in unpredictable cascade effects, feedback loops, and in reactions to hidden vulnerabilities (Bossong, 2014). Failures of complex, dynamic CI networks commonly arise from a relatively slow system degradation, which escalates into a rapid sequence of component failures, potentially a total service outage. The nonlinearity of networked systems manifests such that the first functional disruptions may occur independently. However, during the train of events, the dependent failures may occasion a failure cascade (Eusgeld, Nan and Dietz, 2011).

Notwithstanding the contested credibility of cascading hazard scenarios, the broadly-defined CIP became an agenda of national governments and international organisations involved in transboundary risk management (Hegemann and Kahl, 2018). The legal CI definition within the U. S. framework defined the strategic level of the CIP; it entailed flexibility, long-term viability, and technological neutrality (may be additionally equipped with lower-level policies, guidelines or legal regulations that reflect the current state of technology, causal complexity, and societal preferences) (Harašta, 2018). It encompasses the critical assets protection both as individual physical objects or delimited information and telecommunication system and as an interdependent network (Pursiainen, 2009). Therefore, one may conceptualise CIP as a significant component of contemporary risk governance and regional security governance (Renn, Klinke and van Asselt, 2011).

The contemporary understanding of CIP has continuity with historical precursors of the twentieth century. The rationale of CIP was present already in Europe and the United States during the interwar conceptualisation of strategic bombardment of critical targets. During the Cold War, the protection of strategically significant infrastructures aimed to enhance the ability of CI to withstand targeted attacks and constituted a segment of national defence planning and emergency preparedness subsumed under the "*all-hazards*" and "*total preparedness*" paradigms (Collier and Lakoff, 2020; Dunn-Cavelty and Suter, 2012). The safety management of critical systems increasingly considered the reliability of the incident-preventing and impact-mitigating protection measures quantitatively. These protection measures were drawn-up and effectuated for intervening against all potential hazard scenarios, principally without differentiating between plausible/ implausible, large-/ small-scale incidents. Illustrative are the nuclear safety studies (e. g., "*Reliability analysis of nuclear power plant protective systems*" by Garrick and Gelker, 1967), which showed that the dominant contributors to risk could be beyond-design-basis accidents and thus departing from the "*structuralist*, *defence-in-depth approach*" to safety (consideration of *worst-case* scenarios; classical, but in several settings still undertaken approach without direct quantification of risk). Hence, the probabilistic analyses of risk identify *all feasible* scenarios and their respective impacts. The quantitative risk acceptance criteria are established, and the probability of occurrence of these scenarios (must be acceptably low) is quantified to manage uncertainty and incompleteness of knowledge rationally (i. e. the "*rationalist*, *defence-in-depth approach*" (Zio, 2013).

The current approach to CIP originated in the U. S. in the late 1970s and the early 1980s when threats that did not conform to the Cold War strategic framework, such as energy crises, growing use of nuclear energy, terrorist attacks, or large-scale technological incidents, entered into national security thinking (Collier and Lakoff, 2020). These events necessitated conceiving different preparedness practices, e. g., risk management, to respond to risks with a low probability of occurrence and high magnitude of impact, and difficult-to-deter hazards

(McConnell and Drennan, 2007; Dunn-Cavelty and Søby, 2020). Such approaches, which accentuated the necessity to mitigate the perceived vulnerabilities of interconnected CI, contributed to the basis of the post-Cold War focus on national security.

The tenets of the current CIP programmes originated in the civil defence security area (officially affirmed the 1996 establishment of PCCIP) (Collier and Lakoff, 2020). For instance, the text by (Woolsey, Wilcox et al., 1984) entitled "*America's Hidden Vulnerabilities: Crisis Management in a Society of Networks*" displayed the matured paradigm of CIP by asserting that social well-being, political stability, and economic progress, and military strength of a nation depended on a system of systems. This conceptualisation was conceived by the expert groups of the US Office of Emergency Preparedness and its Systems Evaluation Division (SED) or the Center for Strategic and International Studies (Kupperman and Smith, 1972). The methods produced by SED expert panels included sophisticated system reliability and risk analysis tools with increased reliance on software (e. g., based on Markov processes, Bayesian statistics, or system dynamics-based approaches to analyse complex adaptive systems) to assess CI vulnerabilities and implement risk management techniques or conservation measures for energy crises management (Ouyang, 2013). (Kupperman, Wilcox and Smith, 1975) argued for a priori placement of systematic preparedness measures to expedite the response to future challenges of complex and diverse nature, such as natural disasters or terrorism.

The potential targeting of critical systems' vulnerabilities by terrorists to disrupt the flow of commodities economically crucial to the state was elaborated on by (Kupperman, van Opstal et al., 1982). The reasoning purported in these publications drew on the strategic bombardment theory, whereby the destruction of critical systems could proliferate into the failure of the entire industrial complex. The understanding of the threat environment underscored the non-deterrability of the adversary and broadened the focus of total preparedness, which previously anticipated state-based adversaries. Then, such a broadening had a significant political salience in the view of different energy crises of the 1970s, conflicts in the Middle East, or terrorist attacks in Munich (Collier and Lakoff, 2020).

The four points concerning the CIP stand out. First, despite facilitating the efficient distribution of goods and services, the interconnected infrastructure network exposes modern societies to specific vulnerabilities. Second, the CIP also emphasises the low probability-severe consequence events that insurance schemes may not alleviate (extreme natural events, technological incidents) or non-deterrability (terrorism). The CIP is not restricted to defence against specific, immediate threats but increasingly resorts to preventive security measures.

Third, contingency planning as a method for mitigating vulnerability needs comprehensive design to account for risk propagation enabled by the systemic interdependencies. The preparedness measures consist of investments into system reliability and resilience build-up, scenario-based readiness exercises, and risk analyses to efficiently allocate resources. The emergence of the CIP as a security practice assumes that the current threat environment has become unpredictable, and external and internal security risks to the state have become indistinguishable. The CIP is a domain of government initiative and competency (Dunn Cavelty and Suter, 2012).

3 European critical infrastructure protection

The EU's initiative in coordinating efforts toward critical infrastructure protection is traceable to 2004 and possibly associated with the large-scale crises, such as terrorist attacks in Madrid (2004) and London (2005), influenza pandemics (H5N1/ H1N1), the Icelandic ash cloud, the Euro Crisis, or others, which may have justified the importance of increased crisis management activity at supranational level and capacitated, particularly, efforts in CIP. (Lindström and Olsson, 2009; Dunn-Cavelty and Søby, 2020). In parallel, some states, such as the United Kingdom, France, Germany, the Netherlands, and NATO had adopted the concept of CIP (Abele-Wigert and Dunn-Cavelty, 2006). The EU became equally actively involved in information infrastructure security.

With the political impetus gained from real-world precipitating events (Rhinard, 2019), European Commission (EC) began to actively address CIP following the 2004 publication of "*Critical Infrastructure Protection in the Fight against Terrorism*." EC formulated the European CIP closely connected with counterterrorism policy (Pursianen, 2009). The 2004 Communication provided suggestions for the CI protection preparedness measures to be implemented and proposed further steps to strengthen existing instruments to meet these tasks. It introduced a preliminary definition of the *European Critical Infrastructure* (ECI) in the contemporary threat environment, identified CI sectors, criteria for designating the CI, and the area of security management. The document underscored that each Member State (within their area of competence and the harmonised EU procedures) must identify the critical assets and designate the authorities responsible for security and safety management (Hegemann and Kahl, 2018).

To actualise the proposed protection measures within the mandate of counterterrorism and protection against transboundary crises, the EC launched EPCIP (European Programme for Critical Infrastructure Protection) in 2005. EPCIP outlined plans to identify national CI and designate European CI (at first) in nine sectors and a system of monitoring and inspections (Hegemann and Kahl, 2018). Despite the general acceptance of CIP among the Member States, EPCIP encountered implementation and coordination issues (in the form it was back then defined, especially with the already extant counterterrorist legal measures) (Rehak et al., 2016a). Most Member States and CI owners did not will to implement the demanding and centralised approach to CIP. The emergent policy debate revealed disagreement on the scope of the EU competencies, the hazards and infrastructural sectors to be integrated into the suggested protection regime, the understanding of the CI and the responsibilities of the involved stakeholders. For this reason, EPCIP was reformulated as the "*all-hazards*" framework inclusive of the different threat perceptions among the stakeholders in CIP and underpinned the information exchange and informal coordination (Bossong, 2014; Rehak et al., 2016a).

The lack of clarification of the limits of the EU's political mandate and the disunity in definition and the rules for designation of the CI on the Member State level hampered the emergent CIP policy discourse. The arguments for the broader harmonisation of safety rules did not commence further. Conflict with the different numbers and operational realities of critical sectors identified by the Member States potentially subject to CIP and unclear division of responsibilities may have further obstructed practical policy-making. Moreover, the EU lacked independent means of obtaining confidential data on the operation and failures of the infrastructure; the expert and industry consultations revealed a naturally strong reservation to sharing sensitive security information with a more inclusive set of actors (Bossong, 2014; Pursianen, 2018).

Consequently, in 2006, the EC restricted, for feasibility-sake and high-level political support, the scope of the formal proposal for a directive on the designating of ECI to two priority sectors – energy and transportation (sectors with the observable transboundary linkages and therefore risks). Similarly, the policy-making process was limited to two Commission Directorates. Specifically, DG HOME initiated the CIP policy framework preparation, and DG TREN[1] facilitated the drawing-up of internal guidelines for evaluating the consequences of CI functional interruption. The Council Directive 2008/114/EC was adopted in December 2008. As the chief legal tool of European CIP, Directive 2008/114/EC eventually presented a definition of European CI and the EU's authority. The Article 2 states that:

"*'European critical infrastructure' or 'ECI' means critical infrastructure located in Member States, the disruption or destruction of which would have a significant impact on at least two Member States. The significance of the impact shall be assessed in terms of cross-cutting criteria. This includes effects resulting from cross-sector dependencies on other types of infrastructure*" (Directive 2008/114/EC, Article 2, Paragraph b).

Directive 2008/114/EC contains the guidelines for energy and transportation CI and how to identify ECI. Further, it entails provisions concerning risk analysis and safety management

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[1] In 2010, DG TREN was divided into DG ENER and DG MOVE.

(Annex II), designation of corresponding points of contact for ECI, and preparation of joint security and contingency plans. Relatedly, Article 222 of TEU ("*Treaty on European Union*") demands solidarity and assistance between the Member States in natural disasters and anthropogenic events. TEU also reserved the EU competence to promote the cooperation among the Member States to facilitate the creation of systems protective against such (transboundary) disasters (Article 196). The risk refers to "*the effect of uncertainty on objectives*" (per ISO 31000). The Directive did not explicate the potentially critical events or hazards since they may vary among distinct sub-categories of ECI and the Member States. It is stipulated that the "*primary and ultimate responsibility for protecting ECIs falls on the Member States and the owners/ operators of such infrastructures*" (Paragraph 6 of Directive 2008/114/EC). Despite the lack of definition of potential hazardous events to CI, the Directive 2008/114/EC declares risk analysis indispensable for designating the ECI. The CIP was transposed into the national law under continuous implementation reviews to avoid expectation-capability gaps. After completing the first round of implementation, the Member States planned to examine the possibility of extending incrementally the Directive to other CI sectors.

Per the Commission's 2012 review of the EPCIP, the Directive led to the identification of 14 ECIs – 1 in Transportation – 13 in the Energy sectors. This discrepancy may have exemplified the obstacles to forming a cross-sectoral governance framework of European CIP. Moreover, the first implementation period of the Directive 2008/114/EC may not have produced substantial operational changes or instigated the threat assessment under the novel economic and technological conditions because transport and energy CI had been strictly regulated at the national level already. The Member States' governments already intensively engaged in CIP and with mature preparedness programmes may not have perceived any further added value of European measures and preferred less resource-intensive means than a Directive 2008/114/EC (European Commission, 2012).

According to (Bossong, 2014, p. 213), the scope of the European CIP limited to energy and transportation could have failed to generate substantial political momentum. Furthermore, the critical information infrastructure (CII) was separated from the process, notwithstanding the centrality of cyber-security in contemporary hazard scenarios, and advanced independently on EPCIP (Bendiek, 2012). The EU considered cyber-security a crucial component of economic competitiveness and growth. Subsequently, various cyber-security research projects, the creation of IT industry consultation forums, and the 2004 founding of the ENISA (European

Network and Information Security Agency) supported several legislative tools for criminalising cyber-attacks.

The EU has established informal agencies coordinated by DG HOME, such as the CIWIN (Commission of a Critical Infrastructure Warning Information Network), ERNCIP (European Reference Network for Critical Infrastructure Protection), or the network of national contact points on ECI Protection (Directive 2008/114/EC, Article 17). These agencies were contrived to serve as platforms for discussing good practices, tested procedures, expertise, and harmonisation of technical standards based on voluntary participation, albeit restricted to CI owners/ operators. The originally envisioned competencies of these agencies may have been more extensive, e. g., the original rationale of CIWIN entailed rapid reaction schemes to incidents and the strategy formulation. A high-level platform for consultation on a public-private basis is the E3PR forum. For sectors encompassed in EPCIP, TNCEIP (Thematic Network on Critical Energy Infrastructure Protection) is a thematic branch within the ENTSO-E (European Network of Transmission System Operators for Electricity). The Joint Research Centre focuses, among other things, on the cross-sectoral approach to CIP. Institute for the Protection of the Citizen (founded in 2009 after the Directive 2008/114/EC implementation) has a similar objective (Poustourli et al., 2015).

The initially contemplated extension of the Directive 2008/114/EC to other sectors was not actualised (Pursiainen, 2018). However, the increased efforts have been aimed at European-wide infrastructures that exceed the national risk assessment scope. Since the 2013 revision of the CI protection strategy, the EU has been involved primarily in protecting the systems such as Eurocontrol, Galileo, the power grid and the gas distribution network (Boin et al. 2014). The EU institutions have not thus far become an authoritative reference in the CIP. The EU does not possess a politically senior unit engaged in the formulation and coordination of CIP policies. Hence, DG HOME commonly assigns the ECI Directive review reports to external consulting firms (e. g., Strategy&). Similar institutional deficits are evident (no equivalent CIP representation) in the Council of Ministers (Bossong et al., 2014).

The research, standard-setting, and networking have remained central for CIP. The CIP research projects were funded, e. g., within the EU's *Horizon 2020* or the *Seventh Framework Programme* (FP7, 2007 – 2013); EU co-funding amounted to approx. €40 million to national research initiatives and scientific innovation (hence, not linked directly to national security investments and without specification-/ customer-driven focus). The following EU financial perspective (2014 – 2020) registered an increase in security funding, law enforcement, external borders cooperation, and risk management related to CI, namely through the *Internal Security Fund*. DG HOME indicated that CIP issues could also be present in the regional cohesion funds' investment criteria (Krassnig, 2011). Similarly, the development of the CINEA *Connecting Europe Facility* programme became the key instrument of EU innovation-/ research-oriented funding for energy, transport, and ICT area. Nevertheless, as in the case of institutional capacity, funding allocated directly to CIP is not mainstreamed in large financial programmes.

To summarise, coordination of security practices via scientific and expert networks and technical standards and tests protocols harmonisation has thus far developed more vigorously compared to legislative regulation, making space for the EU's meta-governance of CI (Bossong, 2014). Meta-governance concept (e. g., Søerensen and Torfing, 2009) has been utilised in connection to CIP by (Baker and Stoker, 2012; Dunn-Cavelty and Suter, 2009; CRN REPORT, 2009) to discuss the forms of public-private cooperation in CIP. It may frame the above-outlined description of the European CIP policy debate. Within the context of CIP, the understanding of meta-governance may refer to the attempt of actors (public, here also the EU's EPCIP framework) to prompt and guide the organisation of diverging governance processes or forms of organisation (e. g., distinct hierarchies, markets, instruments, or networks) among other actors. As the preceding text indicates, the EU's EPCIP meta-governance of CIP is constrained in scope and influence (i. e. to scientific and technical expertise, perhaps aiming at creating an epistemic community). As the preceding text indicates, the EPCIP meta-governance of CIP is constrained in scope and influence to scientific and technical expertise in line with its "*all-hazards*" approach, perhaps aiming at creating an epistemic community. According to (Grande, 2012), the general limitations of the EPCIP and Directive 2008/114/EC in attaining the intended outcomes may arise from the high political character of CIP, increasing interdependence among the public and private actors (i. e. the poly-centric nature inherent to security governance) and power and interests' diffusion (also reflected in Dunn-Cavelty and Suter, 2009), lack of dedicated institutional capacity to manage cross-sectoral policy programme, substantial financial stimulus and legal competences (Bossong, 2014).

The state of affairs of the European CIP shifts towards the resilience discourse (Pursiainen, 2018); currently, there is an approved draft of the amendment of Directive 2008/114/EC – the Directive of the European Parliament and Council on the Resilience of Critical Entities (December 2021), which comprises ten CI sectors: energy, transport, banking, financial market, health-care, drinking and wastewater, digital infrastructure and space. The proposal understands resilience as the "*ability* [of CI] *to mitigate, absorb, accommodate to and recover from incidents* *that have the potential to disrupt the operations of the critical entity*" (European Union, 2020, Paragraph 1). Should the Directive be adopted in line with the current draft, it would oblige the Member States to develop a CI resilience strategy (re-evaluation every four years) and identify critical assets and services based on the shared criteria. These subjects will be responsible for identifying any pertinent risks, implementing steps to guarantee their resilience, and reporting any disruptive occurrences to the appropriate authorities. Furthermore, the EC may carry out "*advisory missions*" to review whether the subjects of European significance took steps to satisfy their commitments. The 2018 assessment of Directive 2008/114/EC motivated the drafting of the amendment, finding inadequacies of the current procedures to respond to a dynamic threat environment formed by expansion of infrastructure interdependencies (displayed later inter alia by the COVID-19 pandemic), terrorist threat, insufficient climate change adaptation measures, and diverging legal requirements on CIP imposed by the Member States. The simultaneously issued proposal of the Directive on Measures for a High Common Level of Cybersecurity across the Union (NIS 2 Directive) aims to impose cyber-resilience measures (Council of the EU Press release, 2021).

3.1 Risk analysis in the context of European critical infrastructure protection

The system risk analysis is a framework for assessing risk corresponding to some process or system. Its objective is to provide decision support on the protective actions and design. Risk analysis is a chief component of the preventive approach, which seeks potential hazardous scenarios and evaluates the damage they could cause to individuals, the population, legal entities, the environment, and others (Pollard et al., 2004). Risk is understood as a combination of the probability of occurrence of an (undesirable) event and corresponding damage (in agreement with ISO 31010, but there may be numerous other definitions and approaches available). One may define risk R in line with (Kaplan and Garrick, 1981) as n ordered triples, which describe the sequence of harmful, undesirable events (i. e., hazard scenarios):

$$R_i \equiv (Sc_i, P_i, D_i),\ i = 1, \dots, n; \qquad (1)$$

where Sc is the hazard scenario, P is the occurrence probability (Bayesian), D is an approximation of potential impact (damage) in suitable units, and i is the number of selected scenarios. The listed variables are time-varying covariates; capable of change over time. The subjects involved in the regulation, designing and operation of critical infrastructure may endeavour to manage/ mitigate risk effectively based on the listed scenarios.

Probabilistic risk analysis uses various rigorous and repeatable methods to involve both the probability and consequence of hazardous events to attain representative results of risk. There are numerous ways to display (societal) risk and the acceptability thereof; for instance, risk curves inform of the frequency of surpassing a certain magnitude of impact (e. g., *f-n curves*). Other measures include the *Potential Loss of Lives* (PLL) or *Fatal Accident Rate* (FAR). *Cost-benefit analyses* (CBA) support judgement concerning the material damage. Among the advanced methods of risk analysis currently utilised in research connected to critical infrastructures, one may mention Bayesian Belief Networks (e. g., Misuri et al., 2019), Petri Nets-based approaches (e. g., Zhu et al., 2020), or simulation methods (e. g., Stergiopoulos et al., 2016).

Risk management is closely connected with CIP and refers to "*the systematic application of management policies, procedures and practices to the activities of communicating, consulting, establishing the context and identifying, analysing, evaluating, treating, monitoring and reviewing risk*" (Theocharidou and Giannopoulos, 2015, p. 6; the definition corresponds to ISO Guide 73:2009). The gradual establishment of CIP in the European Union exemplifies a build-up of a coordinated risk management framework for decision processes and expertise-sharing aims primarily to effectuate a rapid response to transboundary crises (Rhinard, 2019). The contribution of risk management seems substantial when dealing with the matters pertinent to the CI, considering the diversity of individual critical sectors and the complexity of information required for a risk assessment.

Risk assessment is a vital part of the EU CIP initiative. Per Article 7(2) of the Council Directive 2008/114/EC, the Member States must regularly report to the European Commission the risks, types of hazards and vulnerabilities for designated ECI. The operator of an ECI conducts the assessment regularly in connection with "*Operator Security Plan*" for a designated ECI (Paragraph 11). The Directive 2008/114/EC provides guidelines for the intermediate steps of the risk management process, i. e. the problem definition and impact analysis (ISO Guide 73:2009). DG HOME provided further methodological considerations in its 2013 working document (general methodological guide promoting systems approach and respective Eurocodes).[2] DG ECHO (2010) created guidelines on the identification of national hazards.[3]

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[2] The 2013 Commission Staff Working Paper "*A New Approach to the European Programme for Critical Infrastructure Protection Making European Critical Infrastructures More Secure*."

[3] The 2010 Commission Staff Working Paper "*Risk Assessment asnd Mapping Guidelines for Disaster Management*."

JRC compiled the report analysing the available risk assessment tools and methodologies at the EU and global levels (Giannopoulos, Filippini and Schimmer, 2012). The report's objective was to compare the state-of-the-art expertise in Europe. It identified a diverse assortment of methodologies and distinguished them according to the scope, audience (CI operators, research institutes, policymakers), and the domain of applicability (critical asset, sectoral, systems) pertaining to the receiving audience also (e. g., systems methodologies that focus at supra-/ national level and target policymakers are less relevant to critical asset operators) (Ibid.).

Based on the Report's findings, most of the reviewed methodologies adopted a "*linear approach*" (i. e., hazard identification and categorization, vulnerability assessment, and impact assessment) and were well defined, tested and validated. The methodologies for assessing the risk to networked systems and interdependencies issues were identified as an area for further refinement (Giannopoulos, Filippini and Schimmer, 2012). Based on the fundamental work by (Rinaldi et al., 2001), the Report differentiated four types of CI interdependencies: physical, geographic, cyber, and logical (extant at both sectoral and intra-sectoral levels) (Ibid.). The 2015 JRC Report (Theocharidou and Giannopoulos, 2015) documents the Directive 2008/114/EC implementation progress with respect to the risk assessment methods at the national level. Moreover, the Report encourages system-of-systems and resilience assessments to complement the traditional risk assessment. To implement these steps, the 2015 Report primarily recommends dynamic, simulation approaches to model CI disruptions at various levels and or the creation of a common repository of tools for risk analysis (e. g., model scenarios, templates, checklists, or harmonised impact scales), particularly for the events with transboundary impacts. As a part of these efforts, the EISAC (European Infrastructure Simulation and Analysis Centre) initiative was inaugurated in 2016 within the FP7 CIPRNet project or the development of the GRRASP geospatial analysis tool (JRC) that aims to provide the Member States with instruments for transboundary risk assessment and identification of common-cause and cross-border scenarios (Poljanšek, 2019; Rossato, 2020).

4 Critical Infrastructure protection in the Czech Republic

Critical infrastructure refers to interconnected and mutually interacting networks or systems containing identifiable sectors and institutions (including procedures and people) and procuring an exchange of products and services crucial to the stability and economic security of the state. Within the identified CI sectors, an element of CI may be, in particular, a building, facility, or public utility. The issues concerning the critical infrastructures were integrated into the Czech legislation by amendment of the Crisis Management Act No. 240/2000 Coll., which became effective on 1 January 2011. The Crisis Management Act amendment transposed the Council Directive 2008/114/EC (Richter, 2014).

The prerequisite for the designation of critical infrastructure is to meet the criteria of critical infrastructure definition according to the Crisis Management Act and the application of cross-sectional and sectoral criteria of criticality outlined in Government Decree No. 432/2010 Coll. *Criticality* is defined as the relationship between the occurrence probability of a particular failure mechanism and the system-wide consequences if the failure occurs (this relationship may be expressed, e. g., as a sum, product, point score). The CI element replaceability in the event of the loss of function and its potential for recovery is evaluated as an additional criterion in the 2010 "*National Programme of Critical Infrastructure Protection*."[4] The Fire Rescue Service of the Czech Republic, ministries, and other central administrative offices conducted the CI identification (Richter, 2014).

CI elements can be designated across different sectors, e. g., the energy industry, water management, agriculture, food industry, healthcare, transport, communication and information systems, banking and financial systems, emergency services, and public administration. In general, the protection of critical infrastructure encompasses measures aiming at reducing the risk of disruption of the function of a CI element. The Crisis Management Act mandates that the legal entity operating the critical infrastructure element (i. e. the subject of CI/ ECI) arranges the protection measures for the critical asset: the development of a "*Critical Infrastructure Subject Crisis Preparedness Plan*" (CISCPP) (regularly inspected by the competent central administrative authority), appointment of Security Liaison Employee, and other arrangements (Rehak et al., 2016a). The chief authority for the CIP programme implementation is the Government, the Ministry of the Interior, or other central administrative authorities, ministries,

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[4] „Národní program ochrany kritické infrastruktury."

National Security Authority, State Office for Nuclear Safety, and the Central National Bank within their remit and the scope of their competence. The protection of information and communication systems is, since 2017, within the competence of the National Cyber and Information Security Agency (Richter, 2014).

The 2015 "*Threat Analysis for the Czech Republic*"[5] includes the risk of loss or disruption of critical infrastructure in general terms, which may be partially attributed to the workings of the EPCIP framework and Directive 2008/114/EC. The first framework for the risk analysis in the Czech Republic developed as a part of Directive 2008/114/EC transposition is the "*Methodology for Ensuring the Protection of CIs in the Production, Transmission and Distribution of Electricity*"[6] (Deloitte Advisory, 2012). The document is based on the 2010 DG ECHO guidelines and a standard ISO 31000 approach. The methodology utilises KARS, a custom semi-quantitative method (point-based risk-scoring matrix), to assess risk and its synergistic and domino effect. The Ministry of Interior and Fire Rescue Service certified resilience methodology before upcoming Directive 2008/114/EC amendment, "*Methodology for Resilience Assessment of Critical Infrastructure Elements*"[7] (Technical University of Ostrava, 2018). The methodology is intended for assessing the CI element resilience, especially in energy, water, transport and communication and information systems. The resilience assessment follows a custom semi-quantitative method CIERA (Rehak et al., 2016a).

4.1 Critical infrastructure in the water management sector

In general, the water management sector is involved in nearly all aspects of the rational use of ground- and surface water resources, preservation of their quality, and protection against the damaging effects of water. The Ministry of Agriculture and the Ministry of the Environment share water management as an area of competence. The 2015 "*Threat Analysis for the Czech Republic*" identified the large-scale disruption of the drinking water supplies among the hazards with unacceptable risk; the Ministry of Agriculture is responsible for the prevention and remedial action. "*The Comprehensive Strategy of the Czech Republic for Critical Infrastructure Issues*"[8] selected water management as one of the priority sectors of critical infrastructures; the primary objective of CIP in this sector lies in securing the supply of potable and non-potable

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[5] "Analýza hrozeb pro Českou Republiku."

[6] "Metodika zajištění ochrany kritické infrastruktury v oblasti výroby, přenosu a distribuce elektrické energie."

[7] "Metodika hodnocení resilience prvků kritické infrastruktury."

[8] "Komplexní strategie ČR k řešení problematiky kritické infrastruktury."

water, preserving and managing surface- and groundwater resources, and operating the wastewater system. Supplying the population with quality drinking water, wastewater disposal, and wastewater treatment are the fundamental prerequisites for the quality of human life. The satisfactory service of water CI is indispensable for social and economic development at local, national, and regional. Moreover, the drinking water production and supply constitute defence infrastructures (defined in the "*Operational Plan of Preparation of the State Territory of the Czech Republic*"[9]).

Water management is a critical sector in the Czech Republic and the whole EU. The organisation of water management within the EU is considerably fragmented; the sector does not exist as one coherent infrastructure (systemic interdependencies are not wholly comparable with the energy or transportation ECI sector). Water provider services within the EU (and the Czech Republic) are predominantly handled by state-owned, municipal or joint-stock enterprises with a dominant state share with a locally- or functionally-limited structure (Řehák et al., 2016b).

The issues connected to the reliability performance, a requisite for maintaining and securing the CI services in the water supply sector, may be distinguished into two subject areas – (1) hydrological regime, handling of water resources in nature, (2) specialised civil engineering structures, facilities, and technical infrastructures built to fulfil the tasks of water management, i.e. *hydraulic structures*. Hydraulic structures are engineering constructions designed and mechanically pertinent for effective control and utilisation of water resources. They are designed to fulfil specific requirements of various water-dependent systems and categorised according to their purpose into *hydro-technical*, *health-engineering* and *melioration* structures. The health-engineering structures ensure, among other things, the supplying of the population, industry, and other users with water. Another purpose is the drainage, accumulation, and treatment of wastewater (Votruba et al., 1993).

The main characteristic of hydraulic structures (also relevant for risk and reliability analyses) is their considerable extent, financial and maintenance demands, and features specific to particular cases. For this reason, it is critical to pay appropriate attention to their reliable design already in the initial phases of their project preliminaries. Underestimated pre-project preparation may lead to inadequate construction design or unmet design parameters and consequently decreased reliability; additional modifications are usually costly and surpass the

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[9] "Plán operační přípravy státního území ČR 2017-2020."

financial demands of adequate hydraulic research during the project phase. Therefore, it is imperative to seek solution variants that will ensure the fulfilment of the designed purposes while minimising the risk of functional disruption, operational problems and costs. Owing to the variety of hydrological, technological, morphological, and other conditions, the properties of any given hydraulic structure are, to a substantial extent, unique. Therefore, the sum of knowledge on the function of a specific hydraulic structure in one area may not be wholly transferable to the design of other waterworks of the same type. Similarly, these specificities are impactful for the reliability assessment of hydraulic structures (Novak et al., 2007; Tanchev, 2014).

4.1.1 Water supply system and its components

The sets of structures and equipment for the provision of drinking water supply for any user include the following parts: (1) the water source and water abstraction (intake) with a possible pre-treatment of abstracted water; (2) the raw water transport to the treatment plant, may include the pumping and objects for accumulation of abstracted water; (3) water treatment processes suited to the customers' requirements (treatment may be omitted if the characteristics of the abstracted water are satisfactory); (4) the transport of treated water to the customer's distribution system (usually involves pumping and accumulation); lastly, (5) the distribution of water to the demand nodes with required flow rate and pressure.

The configuration of a water system and the involved sub-processes may be specific for each real-world case. For instance, some components or subsystems may not be present, while other parts of the supply chain can be sub-divided (aggregated water supply provides water from one source to different locations with separate distribution networks). The industrial water supply system may comprise the same set of components, e. g., to supply cooling water to the circulation system of thermal or nuclear power plants. The water supply system's components are the following: water source, intake facilities, pumping stations, water treatment facilities, water tanks or other storage facilities, transmission mains, and distribution networks. The components, which contribute to the functioning of the water supply process, stretch across an extensive geographical pattern. Each component may exist in various forms and types (e. g., designed to remove different pollutants). The water treatment includes physical, chemical or biological sub-processes to remove impurities from raw water and modify its unsuitable properties (Tesařík et al., 1987; Broža et al., 1999; Baruth et al., 2012).

Current legislation divides systems for the production and distribution of drinking water into two categories: (1) water management critical infrastructures according to Government Decree No. 432/2010 Coll., and (2) general water management (water sources, water treatment plants, distribution systems, and SCADA systems). CIs are identified based on cross-sectional and sectoral criteria. The cross-sectional criteria are employed to consider the severity of the impact of functional disruption of a CI element. Limit values describe the severity of the consequences of the element's disruption (e. g., threshold in terms of loss of life, public health or exceptional economic ramifications) and the functional irreplaceability.

In the drinking water supply sub-sector, the threshold for the CI designation and imposition of a special protection regime concerns the risk of supply interruption to more than 125 000 inhabitants, a fatality threshold of more than 250 persons or more than 2 500 hospitalised persons (per one million persons within the affected area), and the duration of interruption exceeding 24 hours, or economic impact with a threshold value of economic loss to the State of more than 0.5% of GDP (Government Decree No. 432/2010 Coll.). One may add that since the 1990s, the number of Czech inhabitants supplied by public water supply has steadily increased (from 83.2% in 1990 to 94.6% in 2020 (Czech Statistical Office, 2020)). The sectoral criteria are technical and operational values for designating the CI elements within the selected CI sectors. In the water management sector, this includes a water supply system reliant on one irreplaceable source for more than 125 000 inhabitants, a water treatment plant with a minimum capacity of 3 000 $l.s^{-1}$, or a water source with a minimum water storage volume of 100 mils. m^3 (Government Decree No. 432/2010 Coll.).

4.1.2 Water critical infrastructure protection in the Czech Republic

The provisions relevant for the protection of CI in the water management sector further include the Water Act No. 254/2001 Coll. and its amendment No. 150/2010 Coll. The Water Act exists to safeguard surface and groundwater resources and establish the conditions for their economic utilisation; it delineates procedures for protection against the adverse effect of water according to the European Community Law. Section 59 obligations aim at protecting and maintaining hydraulic structures, which may constitute the elements of CI. The protection of the water regime and water resources (including drinking water resources) articulates Chapter V of the Water Act. Drinking water has a substantial impact on human health. Its quality must meet parameters set out in the implementing decrees and the Act on the Protection of Public Health No. 258/2000.

The operation of water supply and sewerage systems is regulated by Act No. 274/2001 Coll., on water supply and sewerage systems for public use. The management of emergencies outlines Section 9 (5). This provision allows the water supply operator to restrict or interrupt the water supply without prior warning in the event of a natural disaster, water supply breakdown, or potential threat to human health or property. However, the water supply operator is obliged to inform and coordinate with the competent public health authority, the water law authority, healthcare facilities, the fire rescue service, and the administration of affected municipalities. The operator provides an alternative water supply within the limits of technical possibilities and local situations (Section 9 (8)). Per Section 21, conditions for emergency drinking water supply are regulated by these legal provisions: The Integrated Rescue Service Act No. 239/2000 Coll., the Crisis Management Act No. 240/2000 Coll., and the Act No. 241/2000 Coll., on economic measures for crises. The water supply service operator is obliged to inform, per request, the Ministry of Agriculture and other state authorities engaged in crisis management on the state of the drinking water supply.

The current crisis management measures during drinking water-related crises contains the 2003 "*Concept of Providing the Population with Drinking Water in Crisis Situations*"[10], published by the Ministry of Agriculture. Relevant methodical instructions and technical standards provide further guidance, as listed below:

- "*Methodical Instruction of the Ministry of Agriculture No. 3468/2021-MZE-15000 of 8 March 2021: On the selection and maintenance of sources for emergency drinking water supply in the system of emergency drinking water supply to the population during emergencies and states of crisis*."
- "*Methodical Instruction of the Ministry of Agriculture No. 74020/2016-MZE-15000 of 22 December 2016 for unified procedure of the authorities of regions, the capital city of Prague, municipalities and city districts in the capital city of Prague to ensure the emergency supply of drinking water to the population during emergencies and crisis situations by the Emergency Water Supply Service*."
- ČSN EN 15975-1+A1 – Security of drinking water supply – Guidelines for risk and crisis management – Part 1: Crisis management.
- ČSN EN 15975-2 – Security of drinking water supply - Guidelines for risk and crisis management - Part 2: Risk management

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[10] "Koncepce zabezpečení obyvatelstva pitnou vodou za krizových situací."

- Decree No. 20/2002 Coll. on the method and frequency of measurement of water quantity and quality.

Concerning the technical requirements for hydraulic structures, the following decrees are particularly relevant:

- Decree No. 216/2011 Coll. on the particulars of handling regulation and operating instructions.
- Decree No. 590/2002 Coll., on technical requirement for waterworks (amended by the Decree no. 367/2005 Coll.).
- ČSN 75 0250 – Basis of design and actions on waterworks structures
- ČSN 73 1208 – The design of waterworks concrete structures
- ČSN EN 1991 – Eurocode 1: Basis of structural design
- ČSN EN 1992-1-1 – Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings
- ČSN EN 1997-1 – Eurocode 7: Geotechnical design - Part 1: General rules

The current safety assessment of the existing waterwork is predicated on the design parameters directed by the provisions on the technical requirements listed above and that were legally binding at the time of the structure's construction and are in the project documentation (i.e. the design parameters with which the structure was designed, permitted and certified). However, significant changes in the technical condition, scientific progress or updating of technical standards may occur during the hydraulic structure's service life. These developments should lead to modifications in the technical design or changes in the operating regime. The current legislation based on the Water Act contains the necessary tools to enforce the relevant safety standards. Specifically, the waterworks such as dams, dikes, weirs, wells, or intake facilities belong to the *safety surveillance and supervision regime*[11] (distinguished into four categories based on the waterwork criticality) and oversight by water law authorities (Section 61 and 62 of the Water Act). The surveillance is conducted throughout the period of design of the hydraulic structure and continues during its operation.

On the already operational structures, this (two-stage) system of supervision by waterwork owners/ operators, qualified personnel (from organisations authorised by the Ministry of Agriculture) and water law authorities should lead to the gradual enforcement of state-of-the-

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[11] Technicko-bezpečnostní dohled nad vodními díly.

art technical standards, specifically during the preparation of the summary stage reports, whereby the relevant safety analyses should work with the latest data, up-to-date methodological procedures and scientific insight. The application and enforcement of updated, usually more stringent safety and technical standards for existing hydraulic structures is accomplished chiefly during their reconstruction and rehabilitation (necessitated by their service life, based on the findings of the regular surveillance for safety-critical waterworks, or imposition of new safety regulations) (Říha et al., 2008).

The reliability-based design and construction of waterworks follow technical standards and European technical standards (Eurocodes). Presently, Eurocodes have been adapted into the national system in most Member States of the CEN (European Committee for Standardization) for harmonisation-sake and are applied in the design of new buildings (do not specify explicit guidelines for the evaluation of existing structures). The original national standards for structural design are cancelled or revised to align national codes with the Eurocode requirements or ISO international standards (Catarino et al., 2016).

The majority of the Czech notable hydraulic infrastructures were built in the period when compliance with the technical standards was legally binding. The formerly binding nature of Czechoslovak technical standards was gradually limited since adopting Act No. 142/1991 Coll. and terminated on 31 December 1999. The current validity of technical standards is regulated by Act No. 22/1997 Coll. (amended by Act No. 71/2000 Coll.). This provision retains the applicability of Czech technical standards (e. g., legislative measures may indicate to or explicitly refer to the need to comply with the entirety or parts of standard procedures or values; standards may become legally binding if issued as a part of a decree). Therefore, technical standards are treated as crucial methodological guidance and predictive tools and are extensively relied upon, whilst the responsibility for applying an adequate technical solution has been transferred to the authorised engineer (ČKAIT, 2017; Melchers and Beck, 2018). The current practice concerning the matter of construction, operation, and safety assessment of hydraulic structures remained, in essence, unchanged from the period leading up to the early 1990s (i. e. when the majority of the water management infrastructure, in particular dam-type water retention structures or water treatment plants, were built). The crucial difference lies in the scope of how to apply the technical standards in a specific design (Říha et al., 2008).

The practicability of actively employing the system of technical standards in the interest of the safety of hydraulic structures is still significant for the state administration authorities in water management when permitting their construction. It is common for standards and Eurocodes to pertain primarily to the design of new structures. Some standards (e. g., ČSN 75 2340) are reasonably applicable to the extending life or supervision of existing hydraulic structures. The reliability assessment of existing structures follows ČSN ISO 13822 (Holický et al., 2013).

The safety and structural reliability of hydraulic structures following the technical standards, particularly during regular operation, is conventionally assessed through the *safety factors* or *limit states*. A safety factor most often is the ratio between the measures of the maximum possible load not leading to the specified structural failure and the expected load to be exerted during the service life (Hansson, 2009). The safety factors are utilised to compensate for uncertainties entering the calculations, which may originate from the physical and statistical variability of the input data, the stochasticity of natural phenomena, the deficiencies in scientific knowledge, and the assumptions when introducing loads and material characteristics. Simultaneously, in the Czech and international standards and methodological guidelines, the required safety factors may not be linked to the expected uncertainties but rather predefined loading states. The disadvantage is the difficulty to differentiate the uncertainties of individual input parameters on the load and resistance side (e. g., material properties). Utilising the *partial factor* method enables the inclusion of selected types of uncertainties; the design formats, representative values for loads, and load combination rules are shown in Eurocode ČSN EN 1991 (Říha et al., 2008).

Structural reliability expresses a structure's ability to withstand loads, the quantifier of which may be a probability (probabilistic structural analysis) (Ditlevsen and Madsen, 2007). The reliability evaluation based on the limit states method includes uncertainties in loads and material characteristics in the calculation. The limit state is designated to differentiate the normal and adverse states; it "*should not be exceeded with appropriate degrees of reliability*" (Vrouwenvelder, 2008, p. 210). The characteristic resistances and loadings values usually have probabilities and return periods prescribed (Ibid.); the ČSN EN 1991 annexes recommend the numerical values for the acceptable failure probabilities (serve mainly as a mathematical tool to compare the reliability of structures and code calibration (Melchers and Beck, 2018). Individual aspects, e. g., the criticality of the waterwork, strength characteristics, and loads) are assigned partial reliability values incorporating uncertainties and scatter of each input and are attuned to the desired level of reliability. The limit states procedure enables integration of uncertainties, unquantifiable from insufficient data and reliability coefficients not given in technical standards (parameters necessitating the further statistical analysis) (Říha et al., 2008).

The existing system of Eurocodes can be applied to designing new structures and provides tools for assessing and managing different load combinations – commonly occurring loads, accidents (e. g., natural gas explosion), and natural disasters (earthquakes). However, it may be problematic to implement for analysing the potential impacts of unforeseeable hazards (e. g., construction errors, unexpected deterioration, or extreme anthropogenic loads). These hazards have been investigated in works concerned with the damage-tolerant design paradigm (Vrouwenvelder, 2008; Megson, 2019). The *robustness* concept frequently appears in the safety-related design of structures per limit states; it maintains that a designed object must not be overly susceptible to local damage, regardless of its origin (extreme loads, insufficient maintenance, intentional damage, and design and construction errors). Various robustness measures and levels of analysis are attributed to different types of structures. The project designer is encouraged to conduct formal risk analyses for the top priority structures per ČSN EN 1991 (Vrouwenvelder, 2008).

The design accounting for unforeseeable incidents and hazards varies from designing protection against/ robustness to commonly-occurring loading states. One may underscore that, in several cases, counterbalancing loads whilst maintaining the equivalent degree of safety may not be feasibly accomplished or economical. Rather, it is advisable to accept local damage to a certain degree and develop measures to ensure that failure is limited to a localised extent and propagates not further in a cascade structural collapse (Vrouwenvelder, 2008). Because failures may occur notwithstanding the compliance with technical standards in structural design, standards should form part of a broader management strategy to reduce the risk that integrates non-structural measures, e. g., by serving as a reference for appropriate execution and quality assurance or supervision (Melchers and Beck, 2018). As one of the possible risk management measures, risk analysis is generally recommended. While systematic and comprehensive risk analysis of hydraulic structures has not yet been conducted or made mandatory, e. g., for damming structures, for water supply systems, such obligation already exists (Říha et al., 2008). However, thus far, continuity planning in water supply infrastructures is at its inception.

4.1.3 European and Czech policy on risk assessment in water supply system

In general, the contemporary water management sector planning in the Czech Republic is implemented under the Water Framework Directive 2000/60/EC, which harmonises action in the water protection and environmental protection; and the Floods Directive 2007/60/EC on the assessment and management of flood risks. The drawing up of a long-term water policy and adaptation of the water management sector to the impacts of climate change on the hydrological regime follows the EU hydroclimatic adaptation strategy; it is realised via the 2007 "*Plan of Main River Basins in the Czech Republic 2007 – 2027*"[12] and the 2020 "*General Development Plan of Areas Protected for Surface Water Storage and the Basic Principles for the Use of These Areas*."[13] These strategic documents were updated in the context of hydrological drought in Central Europe between 2014 and 2020. In the Czech Republic, the water management measures are proposed on the river basin basis and distinguished into national plans for three river basins (the Oder, Elbe and Danube).

Ensuring a secure drinking water supply depends on many factors, such as the quality of raw water, the efficiency of treatment methods, and the integrity of the distribution network. In the contemporary water management practice, mathematical modelling methods are well-established in the design, optimisation and operation of water supply systems. On the other hand, the application of risk analysis theory is thus far at the preparatory stages; the build-up of expertise benefits from experience and methods from other critical industrial sectors. The foremost source of acquaintance with coping with large-scale emergencies, and water-related crises in particular, in the Czech Republic, is connected with the floods that afflicted Central Europe in 1997, 2002, and 2006 (Kavan et al., 2021). Specifically, the 2002 floods triggered prolonged failures in drinking water supplies, and the exposure to flood water-transmitted infections necessitated additional prophylaxis (e. g., Hepatitis A/ B, typhoid, cholera) (Liang and Messenger, 2018).

Water-related hazards were identified in the 2015 "*Threat Analysis for the Czech Republic*" (Kavan et al., 2021). Based on this document, individual type plans were prepared (e. g., emergency water supply plans or flood risk plans). In the aftermath of the extreme floods, the Czech Republic began to pay increased attention to the issue of securing the drinking water supply during crises. The assessment of the Czech Republic's water-related type plans was comprehensively investigated in the text by (Kavan et al., 2021). A significant impetus for implementing the findings of risk theory in the design, construction and operation of water supply systems were the worldwide failure events of the water supply system components and, chiefly, threats of adverse external interventions. Following the events of 11 September 2001 in the United States, large urban agglomerations and complex water supply systems, in

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[12] "Plán hlavních povodí ČR 2007-2027."
[13] "Generel území chráněných pro akumulaci povrchových vod."

particular, are formulating and proposing solutions to issues related to estimating, assessing and managing risks in the supply of drinking water (Janke, Tryby and Clack, 2014). The research into the security of distribution networks began in the U. S. following the events of 11 September 2001, when "*Homeland Security Presidential Directive / HSPD-9*" was issued in January 2004 and directed the Environmental Protection Agency (EPA) to "*develop robust, comprehensive, and fully coordinated surveillance and monitoring systems*" (United States of America, 2004, p. 174). EPA published a "*technical support action plan*" (2004) that outlined the most pertinent research issues and a list of planned research projects (focused, e. g., on intentional water supply contamination events) (Janke, Tryby and Clack, 2014, p. 60).

Similar to the general critical infrastructure protection, European legislation imposed new obligations for the operators of the water supply operators, namely the amended Directive (EU) 2020/2184, "*on the Quality of Water Intended for Human Consumption*," which introduced extensive changes from the previous 98/83/EC text. The Directive entered into force on 12 January 2021; the Member States shall transpose it into national legislation in the two-year horizon. Although the 98/83/EC text included a built-in provision for the European Commission to review the Directive's status every five years and, if necessary, to ensure its amendment, the 2020/2184 amendment was the first substantial change.

The following are the main newly introduced features of the amended Directive (EU) 2020/2184 that will impact the tasks of water supply operators, public health authorities and analytical laboratory staff:

- The risk-based management of the water supply chain should observe the principles of the *water safety plan* methodology (by World Health Organisation, WHO) within the entire catchment area, including the domestic distribution system. The risk assessment would be extended to the water distribution systems in the priority premises. The Member States may determine the priority premises based on subsidiarity (e. g., healthcare facilities, prisons, homes for the elderly, educational facilities, buildings with accommodation, sports or recreational facilities).
- Modification of limit values of existing and establishing of new water quality parameters.
- The identification of potential sources of pollution in water supply sources within the entire catchment areas.
- Water quality matters should be communicated transparently and effectively to citizens for encouraged consumer confidence-sake (Dettori et al., 2022).

The revised Directive set new reference standards for the quality of drinking water in EU countries; its adoption may be conducive to tackling the harmful impacts of pollution on human health. A comprehensive assessment of chemical parameters adjustment of drinking water was conducted by (Dettori et al., 2022); the updates concerning the microbial parameters were reported by (Baudišová and Kožíšek, 2021).

The policy debate towards the Directive's amendment was initiated already in 2003, whence recommendations for the comprehensive risk assessment and preparation of water safety plans were enunciated in the working document by the (Commission of European Communities, 2003). Directive 98/83/EC considered the preventive planning and risk-based approach to water supply system integrity only to a limited extent. The earlier proposed amendments were not accepted at the time because the Member States still had not yet acquired experience with the workings of the Directive in practice (Baudišová and Kožíšek, 2021).

In 2015, the EC conducted a partial amendment (limited to the revision of Annexes II and III), i. e. the Commission Directive (EU) 2015/1787, which integrated the risk-based approach, albeit limited to monitoring aspects. By amending the Annexes to the Directive, the EC introduced preliminarily risk analysis with HACCP or HAZOP methods in preparation for the upcoming integration of water safety plans (WSP). Both methods were already mandatory in the food production sector (DG SANTE, 2015), and after the 2004 modification of HACCP proposed by WHO "*Guidelines for Drinking-Water Quality*" began to be gradually used in water management (Westrell et al., 2004).

The requirements of Directive 98/83/EC were the set minimum for the water supply protection allowing the Member States to implement broader or stricter requirements. A similar approach was adopted by the Directive 2015/1787. In most cases, the Czech Republic took advantage of this right; the advocated principle of risk analysis in the processes of abstraction, production, and distribution of drinking water appeared to be an appropriate legislative measure in the light of the 2014 – 2015 drinking water incidents (Kožíšek, 2016; Paul, 2016). These incidents occurred on water transmission mains and prevented consumers from accessing drinking water or were directly linked to epidemics. The most severe case of waterborne epidemics was in Dejvice (Prague) or Nový Bor. However, the waterborne epidemics are recurrent; water as a frequent vehicle of infection transmission in the Czech Republic was documented based on the ISIN[14] statistics (previously entitled EPIDAT, a database managed by the Institute of Health

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[14] "Informační system infekční nemoci (ISIN)."

Information and Statistics of the Czech Republic[15] (IHIS CR)) and investigated in (Kožíšek, Jeligová and Dvořáková, 2009; Jeligová et al., 2016), particularly in the years 1995 – 2005.

The WHO WSP processing methodology was published in the Czech language.[16] The method for drawing up WSP (water safety plans) based on the WHO guidelines is outlined in ČSN EN 15975-1 +A1. Yet, the voluntary involvement of the water supply operator was progressing slowly. For this reason, the Technology Agency of the Czech Republic (TA ČR) supported the National Institute of Public Health (NIPH) project TD03000155 for introducing risk assessment in 2016 – 2017. Finally, the risk analysis was made obligatory after the transposition of Directive (EU) 2015/1787 and included in Protection of Public Health Act No. 258/2000 Coll., as amended by Act No. 202/2017. The methodological recommendations regarding the risk assessment are outlined in Annex no. 7 to the Decree No. 252/2004 Coll., as amended by Decree No. 70/2018. The risk analysis is presumed to be a starting point leading to the risk management measures (establishing corrective and control measures, verification, and others), and lastly, the minimisation of the risk of compromising the quality and supply of drinking water. The risk assessment obligation impacted the prescribed operating and monitoring rules of health-engineering structures by mandating their regular updating (once per five years at the minimum) and approval by the public health protection authority. The mandatory preparation/ appropriate revision of operating regulations with the risk assessment (included as an annexe) must be accomplished by 31 October 2023 (Orszulíková, 2021).

The original Directive 98/83/EC formed the basis of the Czech drinking water hygiene legislation, the amended Directive's extensive 2021 revision should also modify the Protection of Public Health Act No. 258/2000 Coll. and its implementing decrees (No. 252/2004 Coll. and No. 409/2005 Coll.). It is expected that the Directive's transposition will necessitate amendment of the Water Act No. 254/2001 Coll. and the Water Supply and Sewerage for Public Use Act (No. 274/2001 Coll.) and their implementation decrees (Baudišová and Kožíšek, 2021).

The Directive (EU) 2020/2184 aims at imposing a comprehensive risk-based approach to drinking water safety, encompassing the entire supply chain from the source's catchment area to water intake, water treatment, accumulation, and transmission to the users' distribution network (Paragraph 15). The formulating of water safety plans that adhere to the "*Guidelines and Water Safety Plan Manual*" (by WHO) comprises these steps: (1) identification of hazards

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[15] "Ústav zdravotnických informací a statistiky ČR (ÚZIS ČR)."

[16] "Plány pro zajištění bezpečného zásobování vodou."

associated with the catchment area; (2) preparation of monitoring schemes and counter-measures for each component of the water supply chain; and (3) risk assessment for the priority premises and domestic distribution systems. Following the contemporary risk management paradigm, the process should be subject to continuous exchange of information among the stakeholders (the competent authorities and water supply operators) and regular updating; the risk analysis should pay special attention to long-term processes and large-scale systemic behaviours, particularly the climate change (Baudišová and Kožíšek, 2021; Dettori et al., 2022).

More than ten countries have already accepted water safety plans as an appropriate preventive tool in the water supply sector and made it mandatory in their legislation (e. g., France, the United Kingdom, Sweden, Hungary, and Austria), and numerous drinking water producers prepare them voluntarily. Since 2004, water safety plans have had expert support from the International Water Association. In the Czech Republic, the WSP has been recommended by the sectoral expert conference entitled "*Pitná voda*" (Jeligová et al., 2016). It is necessary to mention that the Directive primarily concerns the qualitative risks. The risk analysis methods envisioned by the Directive are focused on the detection, control and remedial measures of qualitative hazards in the drinking water production process. Qualitative risk is caused by poor water quality, while the quantitative risk in the drinking water supply process results mainly in the shortage or interruption of the drinking water supply. However, in practice, both categories may closely interact. The Directive (EU) 2020/2184 stipulates that the public authorities or other institutions mandated by the state will assume the authorising and supervisory authority for risk analyses. In the Czech Republic, the current transposition draft, i. e. a legislative proposal, foresees this authority to belong to public health protection authorities (Baudišová and Kožíšek, 2021).

In the Czech Republic, the important novelty with respect to the risk analysis or risk assessment lies in the obligation to draw up water safety plans and investigate the risks extant in the domestic/ priority premises distribution system. It is crucial to note that present-state risk analysis uses formalised methods. Because the Czech national law already mandates such procedures (since the Directive (EU) 2015/1787 implementation) and, to some extent, owing to the tradition of the Czech water management, the drinking water is produced and supplied in a relatively reliable and safe manner. Nevertheless, the requirement of mandatory preparation of structured water safety plans may improve or help ensure the safety of the drinking water supply through structured, systematic and transparent rather than empirical and intuitive procedures. A risk-based approach to drinking water production and management must apply to every operator, large and small. Simultaneously, one may underscore that rather than being a new way of ensuring drinking water safety, most of the requirements contained in the WSP methodology are a common component of good water supply practice (Jeligová et al., 2016).

The statutory application of systemic risk assessment may be perceived as a consistent logical framework of good operational practices where they already exist or as an incentive for its implementation. In many cases, the introduction of WSP can bring about a fundamental change, particularly for smaller water systems operated by municipalities (Orszulíková, 2021). According to (Paul et al., 2016), the implementation of WSP may result in a better understanding of the supply system, awareness of the existing risks among operating personnel, and efficient communication among them. Additionally, the WPS may lower monitoring expenses (e. g., owing to reduced frequency of indicators that are not pertinent for a given system), better-targeted investments, and reduced costs of the remedies following incidents (the actual implementation of WSP will require additional investment also).

4.1.4 Water supply risk assessment in the Czech Republic

The following section solves the first part of the first research question: *what are the current state-of-the-art methods for risk analysis of critical infrastructure in the water supply sector?*

A substantial input for the development and implementation of water supply risk assessment was the European research project *Techneau* (EU FP6). The project contributed to identifying and classifying hazards to water supply infrastructure. The National Institute of Public Health[17] (NIPH) was a member of the project's research team. Furthermore, the problem area of the water supply security has been intensively investigated by the Institute of Municipal Water Management (IMWM) of the Faculty of Civil Engineering, Brno University of Technology. IMWM participates in the international *C19 Proactive crisis management of urban infrastructure* organised by European Cooperation in Science and Technology (COST), enabling acquainting with international expertise.

Within the *National Research Programme II*,[18] coordinated by the Czech Ministry of Education, Youth and Sport, IMWM joined NIPH and Vodárenská akciová společnost to organise the *WaterRisk* project (2006 – 2010), which carries out the development of a methodology for the implementation of risk analysis in the public drinking water supply. The

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[17] Státní zdravotní ústav ČR.

[18] "Národní program výzkumu II."

over-arching objective of the project is to support the development of WSP in the Czech Republic (prior to the amended Directive (EU) 2020/2184). However, the notable lack of involvement of the Water Supply and Sewerage Association of the Czech Republic (SOVAK ČR) may have impaired the progress and support of the *WaterRisk* project (Tuhovčák and Ručka, 2007).

The security research of issues connected with the critical infrastructures is actualised, e. g., through cross-cutting "*Security Research Programme of the Czech Republic*"[19] Within this research programme, was included the 2010 – 2015 project denoted as "*The Safety Assessment of Critical Infrastructure Elements and Alternative Possibilities to Increase the Security of Cities and Municipalities in The Drinking Water of Major Natural Disasters and Industrial Accidents*"[20] (VF20102014009). The project's participants were AF-CITYPLAN (Ltd), ViP (Ltd), VODNÍ DÍLA – TBD (JSC), and the TGM WRI (PRI). The project outputs represent the most recent advances for the risk assessment in water management critical infrastructures from the systematic approach.

The resultant methodology for assessing the current state of the drinking water supply systems servicing settlement units, such as municipalities, districts and regions; was certified for the Fire Rescue Service, critical infrastructure operators, and state and municipal administration engaged in contingency planning and risk management. Its purpose is to ensure a principal uniformity in analysing the threat exposure, vulnerability and robustness enhancement options for a given CI sector.

The vulnerability of critical elements to known and commonly occurring threats can be adequately addressed based on the technical standards and rules (building regulations, technical requirements for products). Therefore, the proposed procedure is applicable as a standardised audit for the systematic evaluation of measures proposed or adopted within the framework of water supply contingency planning, i. e. aimed at lowering the likelihood of disruptions or mitigating the potential impacts of a long-term (more than 24 hours) failure of drinking water supply. The project employs the currently applicable Czech regulations and Ministry of Agriculture guidelines as a bedrock. However, it adapts international expertise through

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[19] "Bezpečnostní výzkum pro potřeby státu."

[20] "Posuzování bezpečnosti prvků kritické infrastruktury a alternativní možnosti zvýšení zabezpečení měst a obcí pitnou vodou při vzniku živelných pohrom a rozsáhlých provozních havárií."

European standardisation and Directives and reflects the pertinent Green papers published by the European Commission (Macháček, 2015).

The comprehensive risk assessment and the parameters of the respective technological and organisational linkages were elaborated for these sub-systems – surface and groundwater resources, water treatment, water storage, and distribution to consumers' networks. The methodology consists of five parts (AF-CITYPLAN et al., 2015).

1 Methodology for risk assessment of critical infrastructure with regards to interdependences and synergistic and domino effects.
2 Methodology for assessing the vulnerability of water resources and water treatment plants.
3 Methodology for assessing the vulnerability of distribution systems and accumulation of water.
4 Methodology for assessing of accessibility water for firefighting in territories and industrial zones.
5 Methodology for assessing the vulnerability of specific technological systems and energy sources.

The methodologies were formulated as a recommended systematic working manual. Their structure and intended use underscore the preventive measures and system-of-systems reliability principles and emphasise human safety and sustainable development features. The application in the logical sequence 1, 2, 3 and then 5 fulfils the formalised procedure for assessing the risk of drinking water supply and the hazards with the potential to trigger a state of emergency. The methodologies deal primarily with the possibility of a large-scale technological incident caused by natural disasters (i.e. extreme flood or hydrological drought) and the effects of water contamination, anthropogenic events or ageing infrastructure (AF-CITYPLAN et al., 2015).

The proposed analytical method is the semi-quantitative *Failure Modes Effects and Criticality Analysis* (FMECA). The basis forms a qualitative assessment that comprehensively lists the critical system's elements and associated failure modes. Criticality analysis quantifies the consequences of failure in terms of the probability of occurrence and magnitude of impact using a specified scale. The formal FMECA procedure is standardised in ČSN EN IEC 60812 ED.2.

The methodology's authors included an expert database of default hazards for the selected critical elements and the possible prevention and robustness-enhancement measures (evaluated with *societal cost-benefit analysis*, SCBA). The database was prepared using the *Hazards and*

Operability Analysis (HAZOP); the chosen limit imposed on acceptable risk adheres to the ALARP principle. However, the hazards identification step should fit the context of the situation, local conditions and parameters of the current mission of the specific critical element under consideration. Given their number and the complexity of interaction, four categories of threats are distinguished: natural factors, anthropogenic effects, technical and technological circumstances of the actual operation, and dependencies on the surrounding systems (i. e., to regard potential domino and cascade effect of risk propagation). The proposed method calculates qualitative and quantitative risks in separation (Macháček, 2015).

Given the obligations imposed by the amendment to the Protection of Public Health Act No. 258/2000 Coll., effective from 1 November 2017, guidelines and methodological manuals and default hazard identification and preventive measures were also published in 2018 by the NIPH. Major water supply providers are in the process of implementing NIPH manuals. The output material drew on international expertise, namely the WHO guidelines and the EU-funded (EU FP6) *Techneau* project. The proposed methodology is, in essence, similar to the project VF20102014009 methodological outputs outlined above, i. e. FMECA. However, the VF20102014009 and NIPH manuals follow partially different perspectives. The former was designed for the CI assessment per the requirement of the Crisis Management Act No. 240/2000 Coll. and focuses foremost on the resolution of emergency states causing a long-term (more than 24 hours) disruption of service. Threat assessment appertains to the crisis management authorities and the need for their involvement (i. e. considering the territorial impact of the emergency and time required to remedy it). In other words, the objective of the methodology is to assist the CI operator with identifying risks that they cannot manage by their means (e. g., cascading risks); the operator forwards such an analysis to the crisis management authorities for incorporation into crisis plans (e. g., Crisis Plan of the Region, Crisis Plan of the Municipality with extended powers). On the other hand, the NIPH manual adapts the WHO's water safety plans and generally observes the Protection of Public Health Act (No. 258/2000 Coll.) and Decree No. 252/2004 Coll.

According to (Pumann, Kožíšek and Jeligová, 2016), there may be a distinction between large water supply providers and smaller municipality operators. The current state of the practical implementation of risk analytical methods by water supply operators is suggested and illustrated further. ČEVAK (JSC), one of the largest Czech providers of potable water supply, operates in the Region of South Bohemia and parts of the Plzeň and Vysočina regions. The company supplies drinking water and disposes of wastewater for approximately half a million inhabitants.

ČEVAK prepared its risk assessment methodology and adjusted the operating regulations and maintenance regime to meet the Directive (EU) 2020/2184 requirements. The company utilises the FMECA method, which peruses the outputs of the *WaterRisk* and *Techneau* databases of hazards (adjusted with local reviews) and the NIPH adaptation of the WSP manual. The adjusted methodology adheres to the methodological recommendations of Annex No. 7 of Decree No. 252/2004 Coll. The ČEVAK's expert section consulted the process of updating operating regulations of each infrastructure with public health protection authorities. Therefore, ČEVAK endeavoured to extensively apply contemporary expertise in water supply risk management (Stara, 2021). For large operators, time constraints may be more of an issue in processing the updated rules of operation of health-engineering structures (larger operators will have to re-draw hundreds of operating rules). As such, larger operators may compromise the assessment by automating the process and taking a less individual approach, thereby overlooking the local conditions and specific risks (Paul, Kožíšek and Hloušek, 2020).

Small operators and contractors may find risk assessment abstruse due to the lack of expertise. However, every public water supply operator (i.e. generally with 50 inhabitants at minimum) must have a so-called expert representative (i. e., natural person responsible for the operation of water supply or sewerage systems). Because of the legal qualification requirements that the expert representative must meet, this person should be able to carry out a sound risk assessment, either alone or with the involvement of suitable collaborators (Paul, Kožíšek and Hloušek, 2020). A publication by (Orzsulíková, 2021) draws attention to the problem with implementing risk assessment revealed by the survey conducted in small settlement units (namely, with a maximum of 2 000 inhabitants). Notwithstanding the provisions of Section 6 the Act No. 274/2001 Coll., the designated expert representatives for the water supply operation in the majority of surveyed settlements did not participate in the risk assessment, e. g., owing to the lack of data delivered by the settlement administration or a lack of proper contractual obligation with the water supply operator (Ibid.).

The rest of this section focuses on using the FMEA/ FMECA method. The Czech public sector and the industry professionals engaged in water management (and other sectors also) utilise the FMEA/ FMECA procedure for risk/ reliability evaluation as recommended in ČSN EN IEC 60812 ED.2. FMECA is a top-down semi-quantitative method. It is an instrument frequently applied for studying failures of components and their impacts on the superordinate levels of the system. Surveying the interaction between a macro system and its sub-systems/ components outputs the identification of basic failures. FMECA is a suitable analytical method for systems composed of different technologies, e. g., electrical, mechanical, hydraulic, or software, and varied types of failures. Criticality analysis as an additional procedural step distinguishes FMECA from FMEA (the latter is recommended mainly as a support tool) (Vernez and Vuille, 2009). FMECA can inform supply chain risk management by investigating the link between the potential failure occurrence and its consequence by analysing and computing component criticality (Curkovic, Scannel and Wagner, 2013). For this reason, FMECA is an integral part of the technical design of maintenance regimes in various industries and reliability evaluation; it provides an exact service job content for the personnel by determining the optimal maintenance policy of the most critical components, thereby reducing costs associated with maintenance and contributing to their robustness (Jun and Huibin, 2012; Aven, 2016). (Srivastava and Mondal, 2015) recommend FMECA for predictive maintenance programme.

In the Czech water management expert and administration sector, the FMECA method has been perused conjointly with geospatial analysis for preparing risk maps, e. g., of locations during various flood scenarios during the transposition of the Flood Directive 2007/60/EC (TGM WRI et al., 2009). While the application of FMECA in the drinking water supply sector is at the onset, there is already experience with its use. Additionally, the FMECA software tool is readily available because the analysis is carried out in a spreadsheet environment (FMECA does not require specialised software). The FMECA is a considerably involved team effort; its procedure relies on the sectoral engineering experience of the water supply provider (in contrast to risk maps published as interactive databases, e. g., the DIBAVOD database, which requires low proficiency to use). This analysis systematically identifies the most significant cause/ initiating event and effect relationships; therefore, upon its completion, its results are straightforward to communicate to relevant stakeholders. As such, FMECA provides a basic framework for determining the appropriate measures for risk mitigation.

However, one would highlight its limitations. FMECA is an analytical method (i. e., decomposes a system and analyses it as a combination of components to approximate the whole system) that assumes that a system (here, water supply) behaves deterministically (with a high level of predictability). The deterministic system's states may be delineated using statements or fixed values indicating system parameters. In deterministic risk/ reliability analysis, it is possible to find the instantaneous component state (and, therefore, infer the overall system state) for any time instance in the past or future using only known rules (e. g., equation or law). This deterministic prescription of the design of a system can be delimited by prescribed scenarios or rules. Whether a system adheres to them is evaluated in risk analysis (e. g., the capabilities of a system within the existing design parameters to accomplish the overall safety goal, such as water quality limit values) (Kirchsteiger, 1999; Osadská, 2017).

Therefore, deterministic risk analysis presumes that the system's risk-related behaviour is described adequately with the adherence to checklist-format rules. One may consider the system safe when all possible sequences of hazard scenarios that result in an undesirable event (e. g., service disruption) lie outside the established limits and have such a low probability of occurrence that no precautions are necessary (every deterministic analysis contains probabilistic reasoning). Interactive comparisons among equipment and facilities with the same purpose are rather impracticable. The deterministic approach may provide a limited insight (e. g., for initial screening or design stages), necessary as background information but potentially insufficient for decision-making based on the relative ranking of alternative variants (Kirchsteiger, 1999).

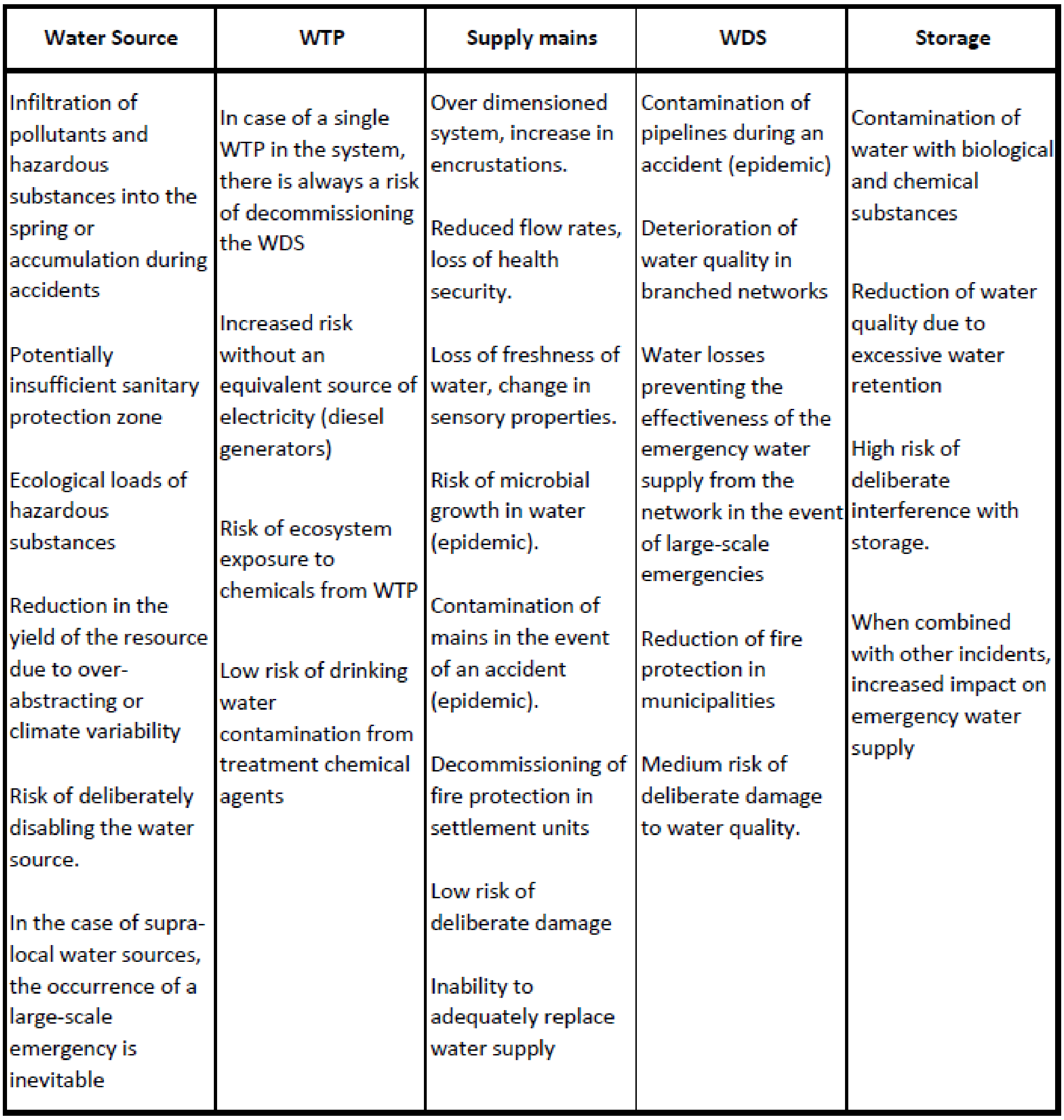
Furthermore, when implementing FMECA, it may be complicated to adequately account for the time sequence of events, dependent failures, renewal processes, the randomness of natural phenomena and environmental conditions, maintenance considerations, and others. System risk/ reliability solution with FMECA may be cumbersome and unmanageable unless there is a direct event chain between cause and effect. The output may be large-scale, even for a relatively simple system. Lastly, the priority setting for criticality evaluation of failure modes may become complicated with several concurrent criticality factors involved. Given the suggested limitations, one would work with the stochastic simulation method in the case study reliability assessment.

5 Hazards to critical infrastructures in water supply sector

The specific conditions of the water supply industry are conducive to a relatively increased vulnerability and risk of disruption for varying lengths of time. The water scarcity resultant from critical infrastructure in a state of emergency may cause a chain of events leading to, e. g., a collapse of services and health facilities. Hazards of natural and anthropogenic origin and forecast inaccuracies threaten each real-world infrastructure system. Furthermore, technical and technological and other threats may contribute to the occurrence of emergencies from synergistic and cascading effects. Increasing the safety of real-world water supply systems necessitates applying a systemic approach to analysing specific conditions using an appropriate formalised method or model (Rosa and Říha, 2013).

Some of the causes of the (partial) failure of critical water infrastructures may arise from the inherent features of water management. However, these functional deviations from the assumptions of original design sometimes cannot be classified as failures per se. These deviations include, e. g., the probabilistic meteorological and hydrological processes in nature (the measurement and observation of which may have been conducted in a short time interval); the limited accuracy of measured parameters (e. g., precipitation or flow rates); the insufficient accuracy of the measured data transmission (e. g., from flow measurement site sensors); imperfect physical or mathematical model of natural processes (the commonly used methods, e. g., generation of synthetic multivariate streamflow or rainfall time series); uncertainty in the long-, medium-, and short-term prognoses of the meteorological conditions, variability of water resources yield and demands; changing priorities in the use of water from different sources; emergency water pollution. These circumstances need to be accounted for to increase the reliability of water management functions in a meaningful way (Votruba et al., 1993).

For a general water supply system, one may identify several critical elements (the damage to or failure of which may result in disruption of the supply or deteriorated water quality) in the following order: catchment area for a given abstraction site at a watercourse or reservoir, intake structure of surface water, extraction structure of groundwater, damming structure, first separation stage in a treatment plant (sedimentation, clarifiers), filtration and disinfection, and storage facilities. Critical linear structures constitute the water transmission sections, such as headrace pipes, supply mains, and distribution conduits (Chudzicki, 2016). Figure 1 compiles some of the possible risks connected with or caused by the malfunction of the critical elements.



Water Source	WTP	Supply mains	WDS	Storage
Infiltration of pollutants and hazardous substances into the spring or accumulation during accidents Potentially insufficient sanitary protection zone Ecological loads of hazardous substances Reduction in the yield of the resource due to over-abstracting or climate variability Risk of deliberately disabling the water source. In the case of supra-local water sources, the occurrence of a large-scale emergency is inevitable	In case of a single WTP in the system, there is always a risk of decommissioning the WDS Increased risk without an equivalent source of electricity (diesel generators) Risk of ecosystem exposure to chemicals from WTP Low risk of drinking water contamination from treatment chemical agents	Over dimensioned system, increase in encrustations. Reduced flow rates, loss of health security. Loss of freshness of water, change in sensory properties. Risk of microbial growth in water (epidemic). Contamination of mains in the event of an accident (epidemic). Decommissioning of fire protection in settlement units Low risk of deliberate damage Inability to adequately replace water supply	Contamination of pipelines during an accident (epidemic) Deterioration of water quality in branched networks Water losses preventing the effectiveness of the emergency water supply from the network in the event of large-scale emergencies Reduction of fire protection in municipalities Medium risk of deliberate damage to water quality.	Contamination of water with biological and chemical substances Reduction of water quality due to excessive water retention High risk of deliberate interference with storage. When combined with other incidents, increased impact on emergency water supply

Figure 1 Sources of critical elements' failure (compiled based on (Kročová, 2008; Kročová and Lindovský, 2012; Chudzicki, 2016). WTP stands for a water treatment plant. WDS denotes the water distribution system.

The first step of comprehensive risk/ reliability analysis is detecting the analysed CI system's failure modes (i. e., the ways a component/ system might fail) and arranging them according to their stochastic dominance (it may be impossible to enumerate all failure modes of large systems) (Melchers and Tang, 1984). When selecting risk/ reliability indicators, one must be mindful of the interactions between the failure modes. In a water supply infrastructure, research is increasingly involved in investigating probabilistic indicators (describing, e. g., the critical loading levels or the component criticality) linked to the events that stimulate the occurrence of the state of emergency owing to the possibility of synergistic and cascading (domino) effects (Awadallah et al., 2014). Each real-world water infrastructure differs in scale, structure and sub-system/ component configuration. For that reason, these systems are not equally vulnerable to threats presented by natural and anthropogenic hazards of like-kind and scope (Haimes, 1998). Furthermore, evaluating risks pertinent to a specified system may not be transferrable to any water supply system owing to their uniqueness and unrepeatedness of local conditions (as such, a thorough analysis of the site conditions must be conducted) (Tanchev, 2014).

The proceeding section enumerates the general hazards with the risk of occasioning a state of emergency within a water supply system with particular reference to synergistic and cascading effects. The research question for this segment is as follows: *for which types of hazards, can a state of emergency be reasonably expected to be declared?*

The *Techneau* and *WaterRisk* projects work with the term "*undesirable state*," which may be, in effect, approximately similar to the state of emergency under Czech legislation. Formally, an "*undesirable state*" arises when an infrastructure loses its design properties or ability to perform its function. Pursuant to the Section 2 (b) of the Integrated Rescue System Act No. 239/2000 Coll., an emergency state "*is the harmful phenomena caused by human activity, natural influences, and accidents that threaten life, health, property or the environment, and require rescue and liquidation work.*"

Construction, technological and project design risk. The sources of risk (hazard) are e. g. the insufficient/ negligent hydrological and hydrogeological survey, unqualified project design solutions, unforeseen effects and loadings due to imperfect exploration strategies. The infrastructure may collapse in the event of disturbance or overloading of the subsoil owing to a design error, malpractice during construction and operation. The bearing capacity of the foundation or superstructure may decrease because of the failure to observe the commissioning test principles or the operating rules (Votruba, 1993; Říha et al., 2008; Hubáčková et al., 2014). The consequences amount to a violation of a legal obligation also, namely the Building Act No. 183/2006 Coll. and other special legislation within the scope of the Water supply and sewerage Act No. 274/2001 Coll. (the provisions on water law authority as the building office) and other. Related is the source of risk (hazard) lies, e. g., in incompatible technology, technological insufficiency, defects, incomplete knowledge of the actual hydraulic efficiency of the system with respect to its physical wear, or hidden water leaks (Votruba et al., 1993; Rosa and Říha, 2013).

External, naturogenic risk, including vis maior. The sources of risk (hazards) are abnormally unsuitable regional conditions, which generally exacerbate the system's vulnerability and reduce its reliability. The occurrences of natural hazards across time and space are best characterised as realisations of stochastic processes that cannot be predicted with an acceptable degree of accuracy. However, one may estimate the probabilities of their occurrence (here understood as relative frequency) with sufficient historical data (time-series observations) (Haimes, 1998). These hazards include e. g., increased seismic activity and mining tremors, undermined areas, slope instability and frequent landslides, active flood plain area, excessive precipitation, frost hollows, winter regime (freezing and or clogging with ice), stream load (dissolved, suspended and bed loads) and others. In the long term, it is necessary to consider the inherent risk due to the hydrological impact of climate change on the available water resource (Votruba et al., 1993; Rosa and Říha, 2013; Shuang, Liu and Porse, 2019).

Risk caused by intentional anthropogenic hazards. The sources of risk (hazards) are difficult to forecast compared to naturogenic threats (floods and droughts happen with frequencies corresponding to return periods); these events are usually classified as having a low probability of occurrence and a high magnitude impact. The intentional anthropogenic threats to water utilities may realise as physical, chemical and biological, and cyber-attacks. The possible sources of include terrorism, war, sabotage, disgruntled employees, frustrated activists, vandalism and others. Physical threats may entail using explosives directed against vulnerable physical components (e. g., intake structures, linear structures) or control centres, resulting in their destruction. Chemical, radiological and biological compounds would contaminate the water in the catchment area of the source, the storage facility, and pipes (e. g., via hydrant). Cyber-attacks may target the SCADA systems in control/ dispatching centres operating, e. g. damming structures, storage facilities, pumping stations, valves or water treatment plants, and compromise the management's ability to regulate water discharges and control chemical dosing according to the prescribed operating rules (e. g., by transmitting erroneous information), and communicate effectively with personnel and emergency services. The impacts of anthropogenic hazards may result in flooding (the so-called *special flood*), endangerment of public health, loss of water supply (affecting industrial, agricultural and drinking water demands), hydropower, environmental damage, diminished fire-fighting capacity, public mistrust, and other. Principally, any water supply system may become targeted by malicious human activity. However, they may not be equally vulnerable and do not offer an equal payoff for the attackers (Haimes et al., 1998; Van Leuven, 2011; Janke, Tryby and Clack, 2014).

Operational risk, including safety and human factors (non-intentional anthropogenic risk). It is a risk of social type, the source of which may be a combination of several factors. The errors in human action may stem from poor risk reflection by operating personnel, lack of qualification, training, inadequate personality and health qualifications, unclear organisational competencies or instruction provided to working personnel and control centres, interventions with insufficient knowledge (established poor practices), overloaded employees, failed backing up (redundancy) of the human activity by another employee, erroneous handling of an emergency and conduct violating the prescribed operating rules. Human factors may be a decisive cause of the occurrence or progression of severe incidents and may compromise the reliability of components (Votruba et al., 1993). The prevention of major accidents is guided by Act No. 224/2015 Coll.

Risk of induced costs for necessary mitigation and compensation measures. Risk management is involved in decreasing risk to a level where further expenditures on risk mitigation become disproportionate compared to the corresponding risk reduction. (Paragraph b, Article 2, Directive 2008/114/EC). This principle of setting a limit to the risk acceptability is referred to as ALARP ("*as low as reasonably practicable*"); it relates chiefly to critical infrastructure elements (within the framework of public sector investment). Compliance with the ALARP principle is mandated by "*Methodical Instruction of the Environmental Risks Department of the Ministry of the Environment for the preparation of the assessment safety report*" pursuant to Act No. 224/2015 Coll.

Risk of technical difficulty and fault repair feasibility. The source of risk (hazard) refers to the probability of delay in the required timeframe for detection, localisation and repair of the defect. The expert estimate must account for the component vulnerabilities within the scope of operational risk analysis, e. g., a higher vulnerability of crossing pipelines or seasonal operational risk during repair (inaccessibility) (Ghavamian et al., 2018). The organisation of repairs is complicated given that hydraulic structures are often located in uninhabited, remote areas (Tanchev, 2014).

Risk resulting from insufficient emergency preparedness. The source of risk (hazard) is e. g. unclear procedures for interaction between water supply system operators and emergency services of the Integrated Rescue System; the absence of or inadequate control and monitoring system of distribution network; unavailability of an emergency source of drinking water, failure to ensure a substitutable source of water or any of the alternative solutions, such as restriction of water abstraction from the water source by declaring regulatory steps, use of alternative water treatment technology, dispatching of water tankers or delivery of bottled water, import of water to a storage facility. The selection and maintenance of sources of emergency drinking water are conducted per the "*Methodical Instruction of the Ministry of Agriculture No. 3468/2021-MZE-15000 of 8 March 2021*."

Risk of cascading effect due to the threat of central electricity supply failure. The source of risk (hazard) of a cascading failure is a failure in one infrastructure that precipitates the failure in other infrastructures. For instance, cascading effect may occur when the water supply system or its components does not have, upon a power outage, an alternative power source with sufficient power. Water CI relies on continuous electricity supply for pumping stations and water treatment plant processes and the SCADA system, which remotely monitors and controls the operation of supply chain components (e. g., valves). This hazard is mitigated by installing diesel aggregates or manual control or less pertinent for systems with gravitational transmission mains. The extent of cascading effect caused by loss of continuous supply of treated water resultant from CI disruption and the subsequent off-line degradation without water service was within the U. S. context studies in dependency analysis by (Porod, 2014). The author concluded that most other CI sectors dependent on water would undergo 67% – 99% service reduction after 4 hours of water supply disruption; critical manufacturing would mark reduced production by 34% – 66% after 6 hours after water service loss. In recent years, the research has developed and formalised various modelling frameworks for complex CI networks connected via different linkages (e. g., physical, geographic, cyber, and logical, according to Rinaldi et al., 2001) and ownership structures: economic theory-based approaches (input-output inoperability model (Barker and Haimes, 2009)); network models (stochastic Petri nets (Ballarini, Donatelli and Franceschinis, 2000)); agent- or complex adaptive systems-based models (e. g., (Baig, 2012)); or models utilising Bayesian networks (e. g., Di Giorgio and Liberati, 2011). Their comprehensive review was prepared in the work by (Ouyang, 2013).

Risk of cumulative and synergistic effect. The concepts of cumulative and synergistic effects were replaced with the term domino effect since the SEVESO II Directive 96/82/EC (currently SEVESO III Directive 2012/18/EU). Nonetheless, the synergistic effect may remain separated in the selected literature. (Rehak et al. 2016c) consider synergistic effects of propagating CI failure via horizontal linkages with the processes and operations in the surrounding area with various levels of impact. For instance, the source of risk may be the concurrence of the hazards from a flood within an active flood plain and the contamination of treated water by pluvial flood water. Other hazards may come from precipitation deficit or stochastically unfavourable rainfall patterns in the region (i. e. the drought hazard), poor catchment management (e. g., intensive agriculture, deforestation causing erosion and sedimentation of reservoirs), or others (Van

Leuven, 2011; Rosa and Říha, 2013). Related is a common-cause failure, which may occur when at least two infrastructures are simultaneously experience disruption form the common-cause, e. g., locally occurring natural disaster (Rehak et al., 2018b).

Risk of domino effects (also encompasses cumulative and synergistic effects under the EIA/ SEA processes). In line with SEVESO III, the domino effect refers to the potential increase in the probability of occurrence or the magnitude of the impact of a major incident because of the proximity of facilities or equipment to the location of a hazardous substance or component. By rule, to prevent the domino effect, the accident and damage from spreading, it may be necessary to conduct an immediate demolition of disturbed structures, blasting obstacles during floods, removal of silt deposits, and others. The failures of water infrastructures may be a source of hazard for the surrounding area, e.g., the accidents caused during the transport of chemicals and their storage at facilities at water treatment plants (Van Leuven, 2011). Other may include the potential occurrence of abrasive phenomena along the submerged area (reservoir shoreline) of the impounding reservoirs, which can disturb the shore for several tens of meters. As a result of the elevation of the weir-headwater level by the weir or the dam, the groundwater flow may be affected, rock slides may occur, and the behaviour of the heaving structure may become unreliable (Votruba et al., 1993).

Risk of escalating effect. An escalating effect describes the situation when a failure that occurred independently in one CI system contributed to the exacerbation of an already present fault at a different critical asset (for instance, by contributing to the fault severity and increasing the time to functional recovery and refurbishment) (Stergiopoulos et al., 2016). Failure of a telecommunications network, which provides the transmission of commands from control centres for terminal elements activation, may give rise to escalating failure. The source of risk (hazard) is the lack of network redundancy in the event of the total loss of connectivity (Rosa and Říha, 2013).

6 Reliability of water distribution network

The last infrastructure in the water supply system is the water distribution network (WDN), which delivers safe drinking water directly to users. The mechanical, hydraulic, and electromechanical components of WDN (e. g., pipes, pumps and water tanks) are interconnected in a considerable spatial expanse. Because pipes and transmission mains constitute the majority of a WDN, substantial initial capital and operation costs of distribution networks may be attributed to installing, inspections, and maintenance of pipes. Pipelines are considered the most vulnerable components as treatment plants, large supply mains and storage facilities have a strict regular monitoring regime, are backed up or consolidated in smaller areas (Kročová, 2008; Chudzicki, 2016). This chapter returns to the second part of the first research question (*What are the current state-of-the-art methods for reliability analysis of critical infrastructure in water management?*) and solves it specifically for the distribution network.

Water system designers and CI operators are increasingly engaged in reliability-based design as the commonly used least-cost solutions have proven inadequate and vulnerable to uncertain future conditions (Giustolisi et al., 2009). Since the failures leading to the functional disruption of hydraulic structures designated as critical infrastructures may result in catastrophic consequences, their reinforcement became a priority. For this purpose, the theoretically scientific and practice-oriented literature has proposed various performance metrics to analyse the performance of the water supply system and its components when subjected to uncertainties. Among them, system reliability is one of the most extensively studied. Research has been committed to developing optimisation algorithms and models for designing WDN. In practice, the optimal design of a WDN and supply chain is an involved multi-objective process considering trade-offs between reliability and cost (Jung and Kim, 2018).

The reliability of WDN is one of the central issues for the water supply providers. Two main questions are particularly challenging in reliability assessment – which reliability descriptors are the most accurate and what degree of reliability is acceptable. The thesis engages the former. The reliability measures the ability of the WDN to fulfil the requirements in terms of quantity and quality while maintaining the operational parameters within the given limits and for a specified period of time and operating conditions (Xu and Goulter, 1998). The required water quantities are the flows delivered at the prescribed pressure conditions. Reliability assessment focused on water quality investigates the concentration of waterborne contaminants that potentially negatively affect human health. The water supply system's ability to meet the quantitative requirements imposed by water users shall be the chief focus (Ibid.).

The reliability of WDN concerning the conveyed quantities works with two main types of failure, which (Xu and Goulter, 1998) denote as "*hydraulic performance failure*" and "*mechanical failure*". The former occurs when the imposed demands exceed the network capacity. The factors contributing to this type of failure may be the nodal demand increases that exceed the design values and or a reduced flow delivery caused, e. g., by the decreased capacity of pipes (Jung and Kim, 2018). Either process may cause the pressure to drop under the permissible level due to head losses at one or more nodes within the network and result in WDN failure. Mechanical failure is associated with system component failures, such as pipe breakage, clogging of valves, or loss of pumps, which reduce the network capacity. The failure occurs when isolated parts of the network cannot meet the required demands at minimum required pressure because of the component failure or components undergoing a repair (Xu and Goulter, 1998).

It is important to note that numerous works approach reliability with various definitions and indicators. However, since both categories of failure in the WDN occur randomly over time and largely independently, the proposed reliability measures need to account for their probabilistic nature (Wagner et al., 1988). Reliability is a general property that may encompass other attributes depending on the system/ component specification (defined, e. g., in ČSN EN 60300-3-15). A commonly listed definition of reliability is the probability that the component performs without failure given a set of conditions, whilst risk is a measure that combines the probability of occurrence and severity of adverse events. Within the "*rationalist, defence-in-depth approach*" to safety management, system reliability analysis is utilised to estimate the occurrence probability of harmful incidents. Further, it informs of the probability that various safety and protection measures designed to mitigate the impacts and control the occurrence of the incident are functioning (Zio, 2013).

In the Czech water management field, reliability is expressed commonly by the "*degree of meeting demands for water*" ["*míra zabezpečení*"], which measures the probability that a guaranteed parameter (e. g., volume of water abstracted per second, year, or other) will not fall below a given value in long-term. This measure expresses consumer satisfaction with delivered demands relative to the designed water supply (established in a project or a water management plan). This characterisation of reliability serves the economic valuation of a reservoir according to ČSN 75 2405 – Water management analysis of reservoirs. Quantitatively, one may select, e.

g., *water supply reliability according to duration*, i. e., the percentage of fully met water demand of the total duration of the considered period. Alternative quantifications are *reliability according to volume* and *reliability according to return period* (Votruba et al., 1993; Peláková and Boersema, 2005).

The factors that impact the reliability of the water supply infrastructures are considerably diverse and impracticable to comprehensively analyse to estimate the overall reliability of the water supply system or its components. Furthermore, the effect of some of the below-listed factor subsets on the operation varies over time, causing temporal changes in reliability. One may distinguish eight groups of factors that influence the reliability of the water supply systems. A thorough survey has been conducted for the first three of the listed factor groups. The remaining factors have been estimated based on a statistical analysis of the failures that have been documented on systems operating under approximately the same conditions. They appear in the order that follows from the project design to the operation (based on (Votruba et al., 1993)):

1 the background and design factors actors that determine the hydraulic regime in the system (e. g., water inflows to and intakes from the system, spatial layout of pipe networks, pump parameters, pipe diameters and roughnesses, dimensions and construction modifications of technological equipment in water treatment plants, water level and volumes of accumulation tanks);

2 the background and design factors concerning water quality in the system (e. g., water quality in water sources, selection of technological equipment, and their dimensions and construction);

3 factors affecting the robustness of the equipment to adverse events (e. g., types of pipe material, methods of connecting and laying pipes, the wall thickness of pressure pipes and vessels, dimensions and reinforcement of building structures according to static calculations, design of suspended, support and anchoring elements, protection against corrosion, measures against malicious security breach);

4 factors relating to the quality of the building materials and technological equipment;

5 factors affecting the quality of the assembly and construction work (e. g., the correctness of the construction and assembly technologies and procedures, compliance of the implemented system with the project designer, compliance with regulations and technical standards for construction and assembly work);

6 factors of the good practices and rational operational management of the system during regular operation and abnormal situations, expeditiousness and efficiency in locating, identifying the faults and their elimination;

7 the observance of the rules of proper and regular maintenance of the equipment and buildings;

8 securing a continuous supply of energy and technological materials (e. g., chemicals in water treatment plants).

6.1 Reliability assessment methods for water distribution network

Reliability modelling of water supply networks is still evolving to reach more accurate results that are more in line with reality; there is no widely accepted methodology for the reliability assessment of WDN (Hisham et al., 2019). The research seeks advances that will lead to improved operation and maintenance of water distribution systems, enhance the existing and find new computational methods for mathematical modelling of WDN. The most frequent subject of research for improving the operation of water supply networks is the location and containment of leakage points in pipes. Water leaks and their timely localisation are a major problem in the worldwide operation and management of distribution systems (e. g., Mazzolani et al., 2016). The recent literature summarising the reliability measures and criteria for WDN includes e. g., (Ostfeld, 2004; Atkinson et al., 2014; Gheisi, Forsyth and Naser 2016). Quantitative resilience methods were systematically reviewed by (Shuang, Liu and Porse et al., 2019). Reliability assessment of WDN covers two categories – topological and hydraulic. Some research utilises surrogate reliability measures also. Their brief review follows.

6.1.1 Topological reliability

The focus of these analytical approaches lies in the topological configuration of WDN. The system vulnerability assessment is then concerned with identifying cut-vertices and cut-edges whose failure (either by incident or intention) would decompose the network. The objective of topological reliability is to examine the connectivity pattern among nodes; it refers to the probability of a network physically staying connected, considering the probability that the components of WDN function at any time under given operational conditions and ensure sufficient connections to link a node to a source (i. e. mechanically reliable) (Ostfeld, 2004). Applied graph theoretic methods were accepted and employed in early WDN evaluation (Jacobs and Goulter 1989; Yang et al. 1996) as a supplementary tool to hydraulic studies.

For instance, (Wagner, Shamir and Marks. 1988) computed "*reachability*" and "*connectivity*" attributes for the topological assessment. "*Reachability*" is a node's characteristic if linked to one source node in a network at the minimum. "*Connectivity*" refers to the probability that *all* demand nodes connect to the minimum of one source. The works by (Shamisi, 1990; Quimpo and Shamsi, 1991) utilised a reliability descriptor entitled "*node pair reliability*" that assigns a specific source node a probability to remain connected to a selected demand node, i. e., the probability of at least one functional path existing between the source node and demand node. The authors envisioned a maintenance regime targeting areas with low calculated "*node pair reliability*" (Quimpo and Shamsi, 1991).

It is essential to underscore that topological measures evaluate only the connectivity between nodes or nodes' reachability. However, they cannot measure and inform about the level of water supply service the users are provided with upon a failure in a network. Functional connection to a source node does not guarantee the provision of required water quantities in a non-failed state, considering the redistribution of pressures and subsequently flows in a WDN upon the failure occurrence (determined by a non-linear relationship between pressure head and flow described, for example, by the Darcy-Weissbach equation). For this reason, topological assessment serves primarily as an initial reliability screening (e. g., for feasibility study) or a supplement to other methods (Goulter and Coals 1986; Wagner et al. 1988; Cullinane, 1992; Shinstine et al. 2002; Atkinson 2013; Trifunović, 2014).

The topological assessment proves beneficial, e. g., to indicate redundancies that contribute to overall WDN reliability. Network reliability is, to an extent, determined by the layout. A redundant network (with the available interconnections) will be more reliable (Goulter, 1987). Works by (Jacobs and Goulter, 1988, 1989) studied the optimal network reliability for a given number of connections in a set of nodes. (Price and Ostfeld, 2015) employed a graph-theory based algorithm conjointly with a hydraulic solver (EPANET) to estimate the optimal pump scheduling (using a skeletonised graph to represent the basic operational logic needed to solve the pump scheduling objective, i. e., the demand node clusters, water tanks operation, and the selection of pumping units with their respective nominal operating costs). The effect of topological properties on water quality was studied by (Torres et al., 2016). Another merit of connectivity-based methods is the lesser data dependence and relative computational efficiency. The application of conventional risk and reliability methods may become complicated for networks with considerable geographical span and complex interaction of system components

(e. g., owing to the lack of necessary data and the unascertained impact of component failures) (Gheisi, Forsyth and Naser, 2016).

The applications of graph theory in WDN research gained increased attention in the water security field in the view of increased awareness of vulnerabilities of infrastructure interdependencies to physical or cyber-attacks. The work by (Davidson et al., 2005) implemented network connectivity matrices produced by the SCADA data to obtain real-time projection on various scenarios of contamination spread. (Amin et al., 2013) explored solutions for reducing SCADA vulnerabilities in WDN to cyber-attacks. The so-called "*evolving threat environment*"((Van Leuven, 2011) outlined in Chapter 2 of the thesis) brought on research engaged in the robustness of network topologies and redundancy measures to minimise service disruptions (Ostfeld, 2005; Perelman and Ostfeld, 2011). Various graph-theoretic techniques for the interdependent infrastructure systems specified for WDN performance assessment were proposed (Duenas-Osorio et al., 2007). Network robustness assessment based solely on topology is present in works by (Yazdani and Jeffrey, 2010, 2012), who build on spectral graph theory and complex topological metrics. They devised their method to detect bottlenecks, structural holes and cut-vertices. The ranking of the WDN component criticality based on connectivity was studied by (Michaud and Apostolakis, 2006; Dunn and Wilkinson, 2013; Meijer et al., 2021). Lastly, within the “*smart*” infrastructure paradigm, (Di Nardo et al., 2014) proposed a WDN sectorisation scheme and optimal flow rate meter configuration with graph theory combined with genetic algorithm heuristics to improve water balance calculation and detect pipe leakages.

6.1.2 Hydraulic reliability

When solving the hydraulic reliability, the centre of focus is the probability that a distribution network can convey the demanded quantities over a specified time and conditions. Therefore, hydraulic reliability engages the primary functional purpose of WDN directly. Because the system experiences randomly occurring faults, the WND reliability analysis needs to respect component mechanical reliability and topological reliability features. A related term used frequently in research is hydraulic availability which pertains to the design of a WDN and describes the probability that a system is in a functional, operating state at a certain time instance, its ability to provide the water supply with an acceptable level of interruptions notwithstanding the normal or abnormal operating conditions (thus, reliability is primarily the ability of the system to fulfil its mission within an assigned period of time) (Cullinane et al., 1992; Yannopolous and Spiliotis, 2013).

(Gheisi, Forsyth and Naser, 2016) subsume hydraulic reliability under the system performance methods that comprise event-oriented techniques and examine the water supply system as a unit that constitutes subsystems or components. Calculating a system's hydraulic reliability entails the information on its component reliabilities and the corresponding failure impacts on the user demands. Since such an objective may become computationally unworkable, evaluation is easier conducted with stochastic simulation (Wagner et al., 1988; Bao and Mays, 1990, Fujiwara and Ganesharajah, 1993). The simulation methods can model the hydraulic or quality properties of the supplied water to obtain an estimate of the probability that a WDN can continuously satisfy the consumer's demand in design quantities and quality in the event of an interruption.

The hydraulic simulation reliability methods evaluate the hydraulic performance of WDN when a mechanical and hydraulic failure occurs. The work illustrative of this approach is, e. g. (Shinstine et al., 2002), which modelled the nodal reliability, i. e. "*the probability of satisfying nodal demands and pressure heads for various possible pipe failures (breaks) in the water distribution system at any given time*" (Shinstine et al., 2002). The authors implemented the "*mechanical availability*" of components, i. e., the proportion of time a system satisfactorily fulfils its function, with the minimum cut-set method (seeking a set of components which, when failed, occasion the system failure; the method investigates topology of WDN and its critical elements) introduced by (Su et al., 1987). The continuity and energy equations are solved implicitly using the minimum cut-set technique combined with a steady-state simulation model. In (Yannopolous and Spiliotis, 2013), the minimum cut-set technique works jointly with a graph-theoretic method to count paths between nodes and determine the hydraulic availability based on fuzzy logic. A different approach was developed by (Fujiwara and Ganesharajah, 1993), who utilised the Markov chain model to represent the evolution of storage tank water levels over time, real-time pump operation, demand fluctuations, and component failures. Reliability is measured as the maximum effective demand served relative to the total demand of the system.

The hydraulic simulation that serves as a basis for reliability evaluation is either demand- or pressure-driven (Gheisi, Forsyth and Naser, 2016). In the *demand-driven approach* (DDA), the hydraulic calculation first determines the nodal demands for a given load condition (i. e., to get the required total quantity of water and the flows in each pipe section). Then, the pressure losses in each pipe section are calculated to obtain the hydrodynamic pressure at each node. One assumes that the prescribed demand is always satisfied in full regardless of the pressure in the network. Although such an assumption simplifies reality, the results may be adequate if no pressure-deficient states occur (Seyoum and Tanyimboh, 2017).

On the other hand, the *pressure-driven demand* (PDD) accounts for the relationship between the nodal flows and the pressure at nodes. Pressure-deficient states occur if the pressure drops at demand nodes below the value of the minimum required pressure (failure occurrence, firefighting demand, or isolation of pipelines during scheduled maintenance). Therefore, demand is a function of pressure. The limit above which demand is no longer sensitive to pressure must be greater than or equal to the value of the minimum required pressure at which all demand is satisfied (Ozger and Mays, 2003; Gheisi, Forsyth and Naser, 2016). These conditions were modelled with various continuous and discontinuous head-discharge functions in works by (Wagner et al., 1988; Fujiwara and Ganesharajah, 1993; Tanyimboh and Templeman 2010; Tabesh et al., 2014). Work by (Seyoum and Tanyimboh, 2017) carried out a PDD analysis with water quality simulation.

Commercial software applications commonly enable demand-driven approaches. Some authors modified them and developed various extensions to approximate the pressure-deficient states potentially extant in WDN upon mechanical failure (Kalungi and Tanyimboh 2003). Moreover, numerous commercial software applications that allow DDA were modified to resemble pressure-deficient conditions (e. g., Ozger and Mays, 2003; Ang and Jowitt, 2006). The EPANET-PDX extension prepared by (Siew and Tanyimboh, 2012) integrates pressure-dependent demands. Other relevant modifications of EPANET with a similar objective may list WaterGEMS (Wu et al., 2006), EPANET-EMITTER (Rossman, 2000), or WaterNetGen (Muranho et al., 2014). Tools independent of EPANET include CWSNET by the University of Exeter.

Works by (Huang et al., 2005; Gheisi, Forsyth and Naser, 2016) may present a reference source for water quality reliability models. Most of the studies published follow a scenario basis. Hydraulic and mechanical failures are reported to contribute to water quality failures (e. g., the pollutant intrusion caused by pressure decrease (hydraulic failure) or fractures formed in pipes or their weakened structural integrity (mechanical failure)). Another field of interest comprises the water age, retention time (e. g., in storage facilities), or residual concentration of disinfectants that occurred because of component failure (Kansal and Arora, 2002).

6.1.3 Surrogate measures

Surrogate approaches deal with network reliability indirectly, albeit via attributes that are reported to correlate with reliability strongly. The justification for using these measures is attributed, e. g., to computational efficiency when evaluating the higher-states reliability of an actual WDN or the lack of data. These methods include the various entropy-based and power/ energy-based techniques, and network resilience indices. The comparative study of various surrogate measures for the analysis of simultaneous multi-component failures in a WDN was presented by (Gheisi and Naser, 2015). Other references were published by the "*Journal of Water Resources Planning and Management*" (ASCE).

7 Water distribution network, a case study

7.1 Problem description

In the case study, one would calculate the reliability of a simple grid network (uniform experiment).[21] The research question for this assignment is: *how reliable is the studied water distribution network, and what measures can be taken to enhance its robustness?* The study network (Figure 2) was utilised mainly as a topological layout template. The U. S. customary units were converted into the metric system. In the case of pipe attributes, the diameters correspond to the U. S. production standard. The grid network is supplied from a single water source (reservoir). The network includes a water treatment plant (WTP) and a pumping station (in this order). Other components of the water distribution network (WDN) are the water tank, two transmission mains (section No. 10 and No. 110), and pipeline sections. The water demands are aggregated into nodes listed in Table 3. The Tables below summarise the parameters of system components. The Q-H curve of the pump in Figure 3 expresses the dependence of the working pressure on the pumped quantity. Water elevation in the reservoir is considered a constant of 230 [m a. s. l.]. The hydrological reliability of the water source is not included in this case study. WTP is simulated as a whole object having overall reliability (its sub-processes and equipment reliabilities are not simulated separately). WTP as a subsystem was analysed separately using simulation methods in these texts – (Taheriyoun and Moradinejad, 2015; Tabesh et al., 2021).

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[21] http://community.wateranalytics.org/t/epanet-how-to-convert-the-unit-in-epanet-using-matlab/1216/2

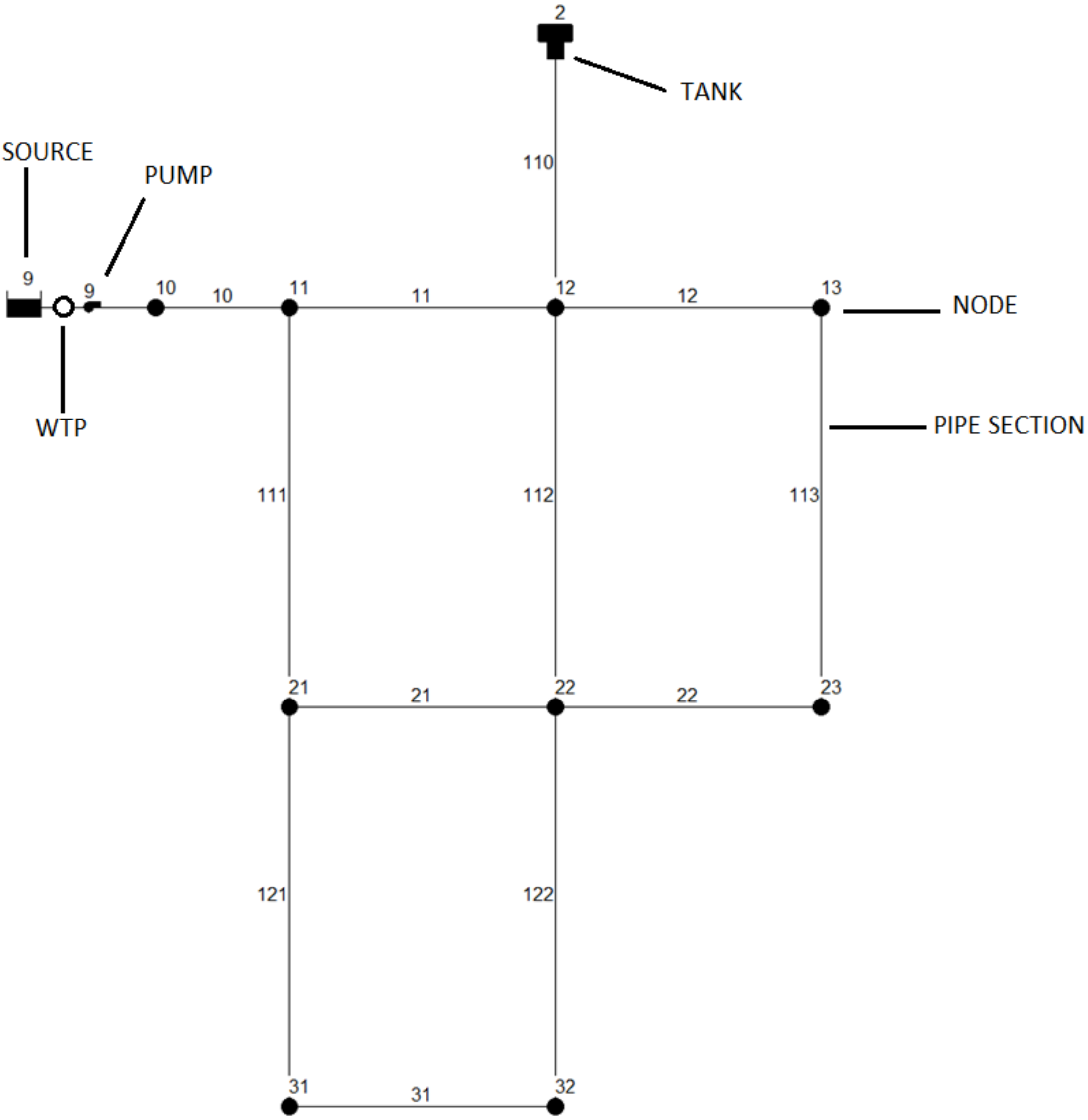

Figure 2 Study water distribution network.

7.1.1 Study network parameters

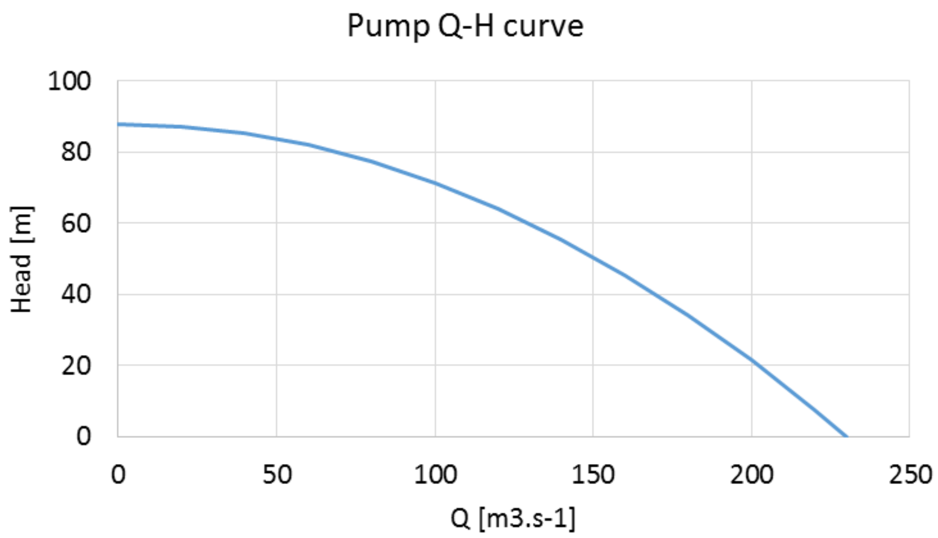

Figure 3 Pump parameter – Q-H curve.

WATER TANK						
ID	Elevation [m a. s. l.]	InitLevel [m a. s. l.]	MinLevel [m a. s. l.]	MaxLevel [m a. s. l.]	Diameter [m]	MinVol [m^3]
2	230	37	31	46	20	0

Table 1 Water tank parameters. *Elevation* describes the altitude of the tank's bottom. *IntLevel* refers to the water level at the start of the simulation. *MinLevel* and *MaxLevel* denote the minimal and maximal water levels in the tank, respectively. The *diameter* attribute is the diameter of the cylindrical tank. *MinVol* is the minimal volume of water in the tank.

PIPES					
ID	Start Node	End Node	Length [m]	Diameter [mm]	Roughness [-]
10	10	11	3209	457	100
11	11	12	1609	356	100
12	12	13	1609	254	100
21	21	22	1609	254	100
22	22	23	1609	305	100
31	31	32	1609	152	100
110	2	12	61	200	100
111	11	21	1609	254	100
112	12	22	1609	305	100
113	13	23	1609	203	100
121	21	31	1609	203	100
122	22	32	1609	152	100

Table 2 Pipe parameters. Roughness is considered the Hazen-Williams roughness of the pipes for determining pressure head loss.

DEMAND NODES		
ID	Elevation	Demand [l.s^{-1}]
10	240	0
11	248	10
12	243	10
13	252	7
21	243	10
22	253	13
23	243	10
31	250	7
32	255	7

Table 3 Demands in the calculated nodes. Demand refers to withdrawal from a given node from the water supply.

7.2 Grid water distribution network

The water distribution networks have (1) topological properties that express the relative positional arrangement of the individual network elements without regard to their dimensions. (2) The physical properties of WDN comprise variables that affect the hydraulic regime of the network (e. g., flows, demands, pressures, water level height in the water tank).

Topologically, a distribution network comprises a set of nodes, some of which are interconnected by sections (i. e., graph). A section of a network represents a section of pipe with a constant diameter and roughness. The demands from and the inflows to the network are located at the section end nodes (Tesařík et al., 1987). A pump is represented by a section (zero-length) also.

The objective of the hydraulic analysis of a WDN is to investigate the necessary information on flow and pressure conditions in a network assigned with a topological layout and component parameters. The hydraulic analysis is utilised in the existing WDN management or their reconstruction and design of new pipelines. Models of the existing distribution system enable reliability assessment to observe the effects of various operational events, such as planned shutdowns, failure of the treatment plant or pumping station and repairs of water tanks or pipelines. The results obtained can contribute to the design of future WDN to better respond to planned and unexpected changes, network expansions, allocation of maintenance, reliability assessment, or others. The model of an existing WDN should be calibrated and verified using the measurement results to receive precise data on the pressure and flow conditions (Abareshi et al., 2017).

The topological structure distinguishes the two basic pipe-network configurations – branch and grid. The study WDN is a grid that consists of pipes connected in circuits throughout the service area. The grid configuration is frequently found in larger municipal areas. It provides a higher degree of reliability because pipe breaks/ repairs occur independently and can be isolated (Wagner et al., 1988). Furthermore, there are several pathways to deliver water from the source to the consumer. The water moving through a grid network is less affected by problems associated with water stagnation and has increased fire-fighting utility (National Research Council, 2007).

The hydraulic analysis in grid networks follows three basic conditions: junction, loop, and friction head loss (eqs. 2 up to 6 are drawn from Tesařík et al., 1987).

Junction condition (eq. 2) is an expression of the law of conservation of mass (or continuity principle), i. e. the volumetric inflows into a junction (node) must be equal to the volumetric outflow from that junction (not valid for dependent nodes, such as water tanks). Inflows to a node are assigned a positive sign, and outflows from a node are assigned a negative sign.

$$\sum Q_i = 0 \tag{2}$$

Loop condition (eq. 3) is an expression of the law of conservation of energy. The sum of the oriented head losses in all sections in the loop is zero. If the direction of flow in a given section is the same as the loop orientation, the head loss is assigned a positive sign. If the direction of flow on that section is opposite to the loop orientation, the head loss on that section is assigned a negative sign.

$$\sum h_i = 0 \tag{3}$$

Head loss of a hydraulic system are divided into minor losses and friction (major) head losses. Minor losses are caused, e. g., by changes in direction, changes in pipe profile and occur locally in valves. Usually, they can be omitted from the calculation of the WDN. The decisive factor is friction head loss, which is determined according to the Darcy-Weissbach equation:

$$h_f = \lambda \frac{L}{D} \frac{v^2}{2g} \tag{4}$$

where λ is the friction coefficient, L is the pipe length [m], D is the pipe diameter [m], and v is the flow velocity [m.s^{-1}].

Turbulent flow occurs virtually always in water supply systems (Tredao et al., 2007). As such, the friction coefficient λ may be obtained from Colebrook-White equation:

$$\frac{1}{\lambda} = -2\log\left(\frac{\Delta}{3.7D} + \frac{2.51}{Re\sqrt{\lambda}}\right) \qquad (5)$$

where Δ [m] is absolute piping roughness and Re [-] is the Reynolds number, which is expressed as:

$$Re = \frac{vD}{\nu} \qquad (6)$$

where ν is the kinematic viscosity of water [m^2.s^{-1}].

One must be mindful that EPANET models work by default with the Hazen-Williams equation to determine friction head loss, which is typically used in the United States and is factually compatible with the above relationship. The adjusted equation for SI units was derived by (Karney, 1999):

$$h_f = 6.840 L v^{1.85} C^{-1.85} D^{-1.65} \qquad (7)$$

where C is the Hazen-Williams friction coefficient [-]; its values are listed in Table below.

MATERIAL	HAZEN-WILLIAMS C [-]
Cast iron	130 – 140
Concrete or lined concrete	120 – 140
Galvanised iron	120
Plastic	140 – 150
Steel	140 – 150
Vitrified Clay	110

Table 4 Values of the Hazen-Williams friction coefficient C for different pipe material (source: Rossman et al., 2020).

7.3 EPANET 2.2

The case study uses EPANET 2.2 for the hydraulic analysis of the study network. It is a widely used public domain software application designed for solving pipe networks. It enables static and quasi-dynamic hydraulic analysis of Newtonian fluids in pressurised pipe networks and qualitative analysis of water delivered through the WDN. Because EPANET enables Monte Carlo simulation (and the scale of the simulated network is not limited), it is possible, among other things, to assess alternative (risk) management strategies aiming to improve the network's robustness. The EPANET has a relatively user-friendly interface and can be run from an external program. Its working environment allows the user to enter data and create a model in the X and Y coordinate system and report results in various forms. One may perform a static hydraulic analysis for the defined model. Otherwise, for the quasi-dynamic analysis, it is necessary to specify the water demand variation (during the day, year or other), the pumping time course, or the failure and repair times. The calculated results will be the hydrodynamic pressure in each time step in all nodes of the simulated network, the water level in the reservoirs, the flow rate and the head loss for the pumps. With random failures in the network implemented, the main result of the simulation is the WDN reliability.

7.4 Reliability parameters

Reliability refers to the probability that a system performs a required function without interruption, for a given time period and under given conditions. This capability is a complex property of a given system and is expressed by probabilistic variables, where the randomly generated variables are *time to failure* (TTF) and *time to repair* (TTR). TTF is a continuous random variable that is the time passing from when the component begins to function until its first instance of failure. By itself, TTF models the service life of a non-repairable unit. TTR is a continuous random variable representing the time required to repair a component after it fails (Xing, Levitin and Wang, 2019). These two probabilistic indicators would be described using exponential distribution. The utilised quantitative reliability indicators for a repairable element are include failure cumulative distribution function (CDF) $F(t)$, failure probability density function (PDF) $f(t)$, reliability function $R(t)$ (also called *survival function*), and failure rate $\lambda(t)$. The calculation of these indicators is as follows (eqs. (8) up to (10) are drawn from (Xing, Levitin and Wang, 2019).

The failure function of a component is given as the CDF of random variable T

$$F(t) = P(T \leq t) = \int_0^t f(x)dx \tag{8}$$

where $f(x)$ is the PDF of T. $F(t)$ denotes the probability that a component fails within time interval $(0, t\rangle$.

The reliability function of a component at time $t > 0$ is:

$$R(t) = 1 - F(t) = P(T > t) = \int_t^\infty f(x)dx \tag{9}$$

Reliability function expresses the probability that a component does not fail in time interval $(0, t\rangle$ and is still functional at time t.

The failure rate is a function that measures a component's "*instantaneous speed of* [...] *failure*" (Xing, Levitin and Wang, 2019, p. 11):

$$\lambda(t) = \frac{f(t)}{R(t)} \tag{10}$$

7.4.1 Exponential distribution

A component that entered into operation at time $t = 0$ is considered. Assuming the exponential distribution, the TTF of the component has a PDF with a parameter λ. The eqs. (11) up to (14) are drawn from (Votruba et al., 1993).

$$f(t) = \lambda e^{-\lambda t} \tag{11}$$

A component with exponentially distributed TTF has a constant failure rate $\lambda(t) \equiv \lambda$, where λ is the number of failures per unit of time.

The failure function is:

$$F(t) = P(T \leq t) = \int_0^t f(x)dx = 1 - e^{-\lambda t} \tag{12}$$

The reliability function is:

$$R(t) = P(T > t) = \int_t^\infty f(x)dx = e^{-\lambda t} \tag{13}$$

The mean time to failure (MTTF) is:

$$MTTF = \int_0^\infty R(t)dt = \int_0^\infty e^{-\lambda t}dt = \frac{1}{\lambda} \tag{14}$$

The components, whose TTF and TTR are exponentially distributed (constant failure rate), are not affected by ageing. In their case, the probability of a failure occurring at the next time instance does not depend on how long has the component been operating in a non-failed state. The application of exponential distribution is suitable for components that meet the assumption of a constant failure rate at least during the normal operation (after the burn-in period) with regular monitoring and maintenance. The waterworks under consideration adhere to a regime of maintenance, regular modernisation and safety inspection to ensure their operational sustainability. The exponential distribution can further be assumed for a component whose failure is caused by external factors. The failure occurrence is associated with the deviation of a certain ergodic random process surpassing a given acceptable level (Votruba et al., 1993).

7.4.2 Renewal process

The components considered in the study network are repairable. Therefore, when analysing the reliability of this technical system, one has to acknowledge the renewal function of the system or a given component after a failure. The renewal process is the sequence of non-failed and failed states of a random process (continuous-time, discrete state-space). These processes are relatively simple in their structure, and reliability indicators derived from them are relatively easy to put into final numerical form. At the same time, however, they are a good representation of the real-world function of many objects (Epstein and Weissman, 2008).

At the beginning of the process, the component is in a non-failed state. The non-failed state has the value $X(t) = 1$ assigned. The component remains in the non-failed state for time τ_1. At time instance $t_1 = \tau_1$, a failure occurs. Then, the component is in the failed state, to which the value $X(t) = 0$ is assigned. The failed state remains until the time instance $t_1' = \tau_1 + \tau_1'$, when the non-failed state is renewed. The system that over time alternates between two states (1 and 0) is modelled by *alternating renewal process* (Poisson process) (Epstein and Weissman, 2008).

7.4.3 Reliability of series and parallel systems

The focus of the modelling of the study WDN considers the reliability of its components. Increasing the reliability of the entire system is one of the motivations for conducting reliability analysis. Enhancement of reliability may be attained by a suitable system design, increasing the reliability of individual components, or backup of critical components or subsystems. The study network is a grid that consists of a combination of segments arranged in series and parallel. The selected risk-mitigating strategy is backing up the sensitive components with redundancies (installing redundant components in parallel).

In a *series system* configuration, if any system component fails, the entire system fails. A series system is operational only if all its elements are operational. The structure function of a series system is (Thoft-Christensen and Murotsu, 1986):

$$\phi(\boldsymbol{x}) = \wedge_{i=1}^{n} x_i = \min(x_1, x_2, \ldots, x_n) \tag{15}$$

The reliability of a series system (components have different, exponentially distributed failure rates) is (Romeu, 2004):

$$R(t) = R_1(t) \ldots R_n(t) = e^{-\lambda_1 t} \ldots e^{-\lambda_n t} = e^{-\lambda_S t} \Rightarrow \lambda_S = \textstyle\sum_{i=1}^{n} \lambda_i \tag{16}$$

In *parallel system* configuration, as long as not all system components fail, the entire system is functional; therefore, a parallel system is operational if at least one of its components is operational. The structure function of a parallel system is (Thoft-Christensen and Murotsu, 1986):

$$\phi(\boldsymbol{x}) = \vee_{i=1}^{n} x_i = \max(x_1, x_2, \ldots, x_n) \tag{17}$$

The reliability of a parallel system (components have different, exponentially distributed failure rates) (Romeu, 2004):

$$R(t) = 1 - \prod\left(1 - R_i(t)\right) = 1 - \left(1 - R_1(t)\right) \times \left(1 - R_2(t)\right) \times \ldots \times \left(1 - R_n(t)\right) \tag{18}$$

$$R(t) = 1 - \left[1 - e^{-\lambda_1 t}\right] \times \left[1 - e^{-\lambda_2 t}\right] \times \ldots \times \left[1 - e^{-\lambda_n t}\right] \tag{19}$$

7.5 Reliability of water distribution network

To solve the reliability of the study network, one would consider two types of failure: (a) pressure (hydraulic) failure and (b) pipe failure.

The derived parameters of the water supply networks are the pressure heads at the demand nodes and the withdrawals from the supply nodes (or the inflows to the supply nodes); the parameters for the pipe sections are the flows, head losses and mean flow rates in the sections. For the estimate of the WDN reliability, the most important parameters are the pressure heads. Pressure heads are used to determine the reliability using the following expression:

$$R_j = P\left[H_j \geq H_j^*\right],\ j = \{1, 2, \ldots, n\} \tag{20}$$

where j denotes the demand nodes in the WDN. For every demand node there is a minimum required pressure head H_j^*. The reliability indicator for the demand node in the WDN is the probability that the pressure head in the demand node does not fall below the minimum permissible value in the given time period. The *minimum* required pressure is 0.2 MPa (per

ČSN 73 0873). The *maximum* required pressure at the lowest elevation of the water supply network must not exceed 0.6 MPa (for all pressure zones; per Decree No. 428/2001 Coll. implementing the Water Supply and Sewerage for Public Use Act No. 274/2001 Coll.). In exceptional short-term cases, the maximum required pressure may reach 0.7 MPa.

The derived parameters of a network's element are calculated from the given parameters of all the WDN components. In other words, the water supply network is always analysed *as a whole* – no network element is considered in isolation from other network elements.

When assessing the random states of the network, the occurrence of failures that take a section, several sections or part of the network out of service must also be taken into account. These usually occur, e. g., owing to pipe breaks or valve failures, pipe punctures due to corrosion, breaks in the seals of pipe joints or valve clogging. Each section of the network is assigned a probability with which the section is put out of service at a specified time instance due to a failure.

If T is the total monitoring time of the pipeline and τ is the time period, during which the monitored pipeline was taken out of service due to a failure, the reliability, i. e. the probability that a pipe section of the network will *not* be taken out of service due to a failure at any time instance, is given by:

$$R = \frac{T-\tau}{T} \tag{21}$$

Eq. (21) also calculates the mechanical reliability of the whole network.

Therefore, one would define the reliability of the study network as:

$$R_j = P\left[H_j \geq H_j^*\right] \text{ OR } P\left[Q_j \geq Q_j^*\right], \quad j = \{1,2,\ldots,n\} \tag{22}$$

The reliability of WDN is the probability that the pressure in demand nodes does not fall below the minimum required level H_j^* or that the networks components remain functional, thereby capable of delivering the required quantities Q_j^* (eq. (22)).

Note: the reliability assessment outlined above was suggested and tested in (Wagner et al., 1988; Votruba et al., 1993; Xu and Goulter, 1998; Hisham et al., 2019). One would underscore that the process of a WDN reliability estimation depends on the definition of reliability first and foremost. For instance, a different solution to WDN reliability was proposed by (Goulter, 1995). Here, the author measures reliability based on deficits in the volume of water supplied. Alternatively, (Lindhe et al., 2009) utilised *Customer Minutes Lost* as a measure of reliability.

7.5.1 Simulation

The stochastic modelling of water supply networks uses the Monte Carlo simulation – repeated random sampling of events a large number of times to obtain the estimates of the system's reliability indices solutions using artificial realisations of the actual processes with additional recurring randomness (drawn from the system's discrete phase space) (Zio, 2013). A real-world water supply network is a flow of continuous random variables varying in time. EPANET simulation uses temporal discretisation, i.e. splitting the flow into time steps. Monte Carlo simulation is particularly viable when the exact value of results cannot, owing to the statistical properties of the events, be calculated with analytical procedures. Furthermore, while analytical methods may be advantageous for determining the probability density function or the failure rate for the system's components, analytical analysis of a complex system may simultaneously increase the complexity of the solution and computation. Therefore, the main advantage of the simulation approach lies in the potential to investigate the real-world processes in a variety of scenarios that would otherwise be difficult or impossible to approximate analytically, regardless of the analysed WDN scale and dimensions.

7.5.2 Data

For the case study, the failure and repair rates of water supply system components were obtained from the "*OREDA Offshore Reliability Data Handbook*" (4th edition; SINTEF Industrial Management, 2002), the "*COMAH Safety Report Assessment*" published by the U. K. Health and Safety Executive (HSE, 2017), and "*Forecasting failure rate of water pipes*" by (Kutyłowska, 2019). The reliability indicators of the water treatment plant were estimated. The reliability of a water source, a reservoir, should agree with the norm in ČSN 75 2405 – Water management analysis of reservoirs. However, the hydrological reliability of the water source in the study network was omitted. Therefore, the source is assumed to be 100% reliable.

COMPONENT	FAILURE RATE	SOURCE	FAILURE FREQUENCY
Water treatment plant	0.05 [y^{-1}]	Estimated	Once per 20 years
Pumps	6.54 x 10^{-5} [h^{-1}]	"*OREDA Offshore Reliability Data Handbook*" (SINTEF, 2002)	Once per 2 years
Water tank	1 x 10^{-4} [y^{-1}]	"*COMAH Safety Report Assessment*" (HSE, 2017)	Once per 1 year
Pipes	0.4 [failure/ $km^{-1}.y^{-1}$]	"*Forecasting failure rate of water pipes*" (Kutyłowska, 2019)	Once per 2.5 years

Table 5 Failure rates used in the case study simulation.

7.5.3 Results

The simulation worked with three selected variants:

Variant A	FR (pipes) = 0.4 [failure.km^{-1}.y^{-1}] = 4.10^{-4} [failure.m^{-1}.y^{-1}]
	One pump operates in the WDN.
Variant B	FR (pipes) = 0.1 [failure.km^{-1}.y^{-1}] = 1.10^{-4} [failure.m^{-1}.y^{-1}]
	One pump operates in the WDN.
Variant C	FR (pipes) = 0.4 [failure.km^{-1}.y^{-1}] = 4.10^{-4} [failure.m^{-1}.y^{-1}]
	Two parallel pumps operate in the WDN.

Table 6 Selected WDN robustness-enhancing variants. *Variant A* is the basic scenario. *Variant B* is a pipe modernisation scenario. *Variant C* is a redundant pump installation scenario. *FR* stands for failure rate.

Note: Transmission mains No. 10 and No. 110 are backed-up with redundancies because these are critical elements of the WDN. One assumes that failure (i. e., does not convey water) of main No. 110 occurs concurrently with water tank failure. The main No. 10 fails only with a water treatment plant or pumping station failure.

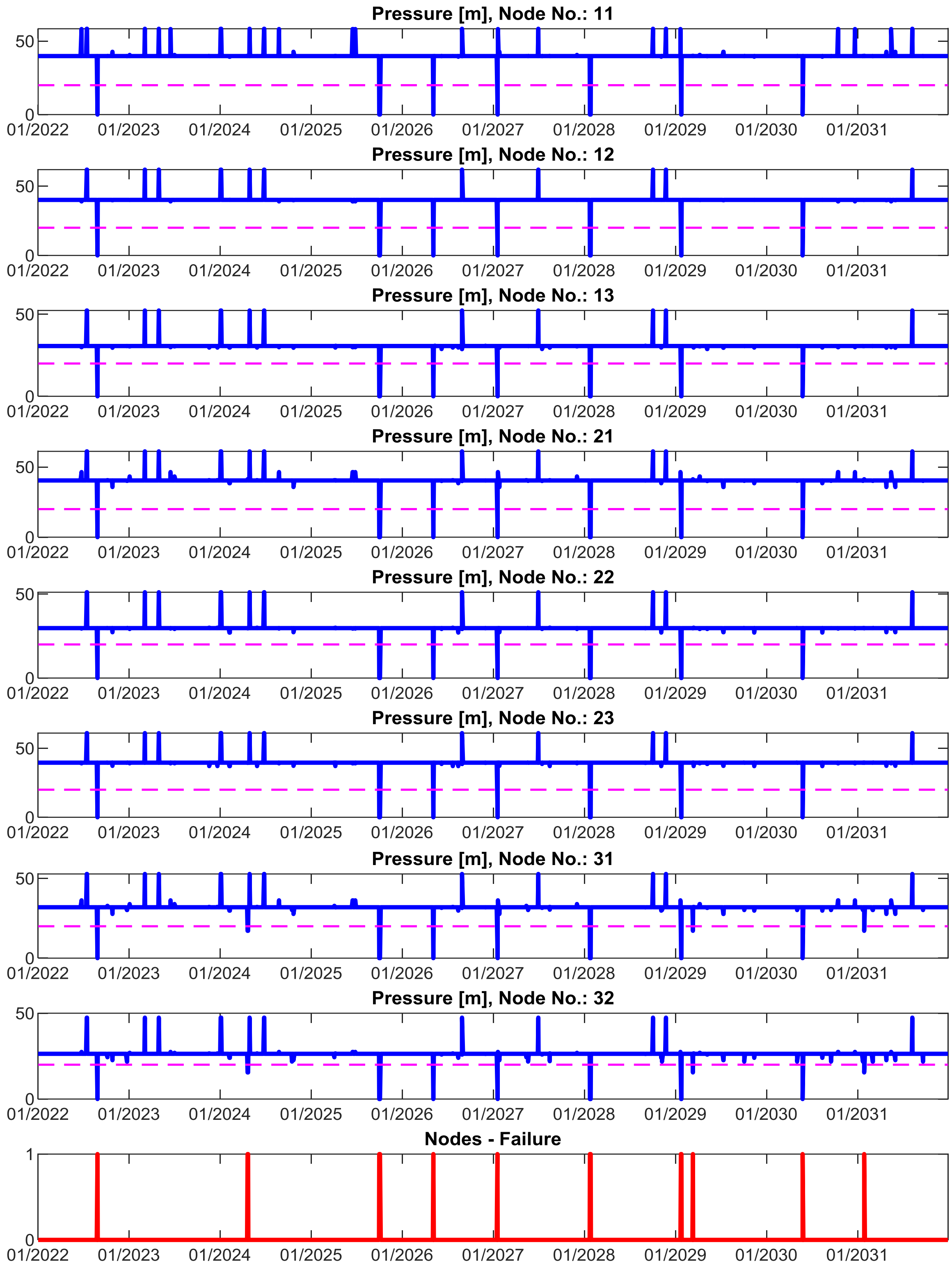

Figure 4 Pressure states at calculated nodes. Blue solid line represents the pressure at nodes. Magenta dashed line mark the level of minimum required pressure head H_{min} = 20 m (given by a technical standard). Red solid line informs of the overall failed state (1 – failed state, 0 – non-failed state) of the WDS nodes (the figure at the bottom is a combination of the figures above).

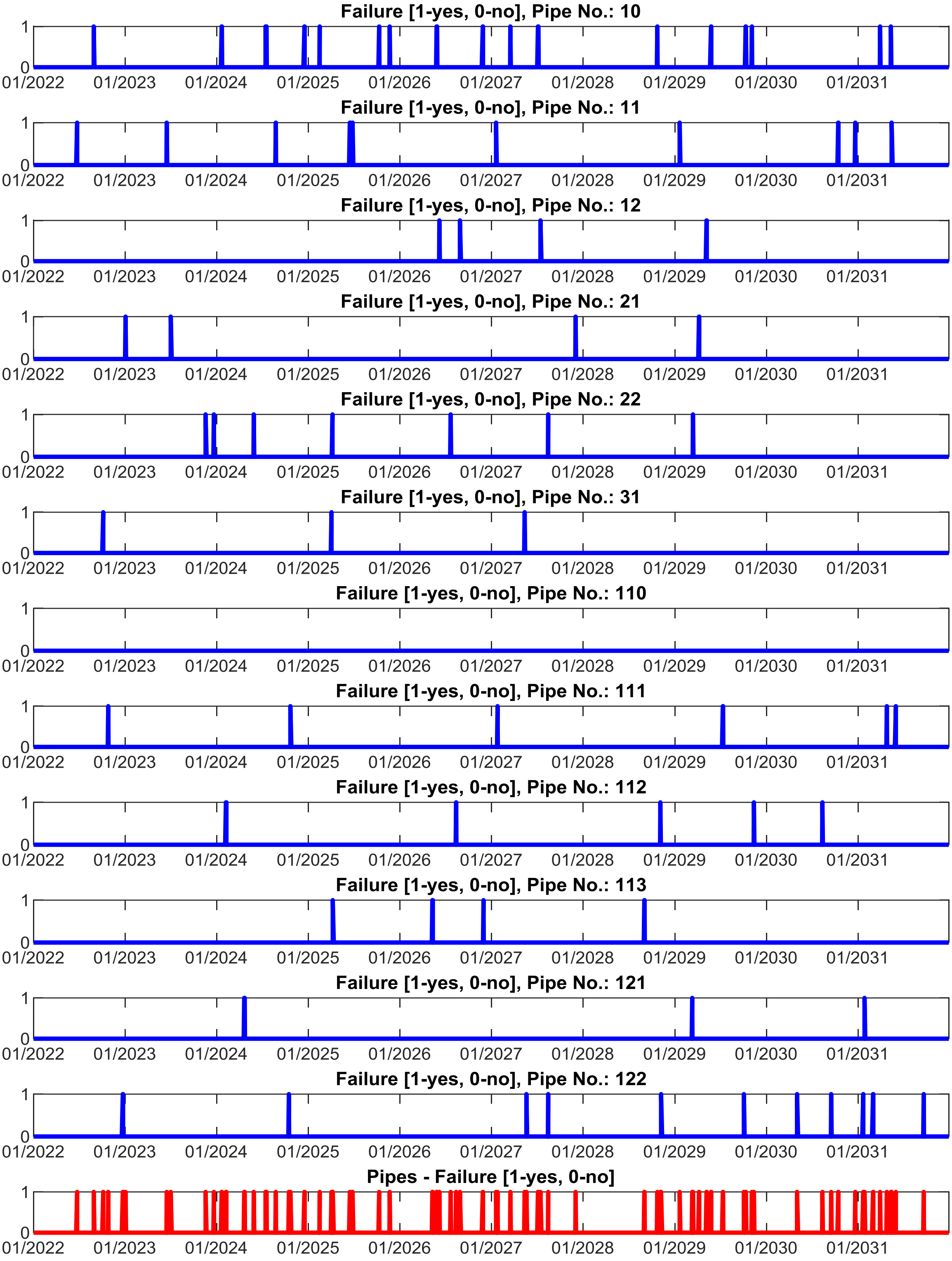

Figure 5 Mechanical failures of pipe sections. Blue solid line displays the mechanical failures of individual pipes. Red solid line informs of the failed states of all pipes (the figure at the bottom is a combination of the figures above).

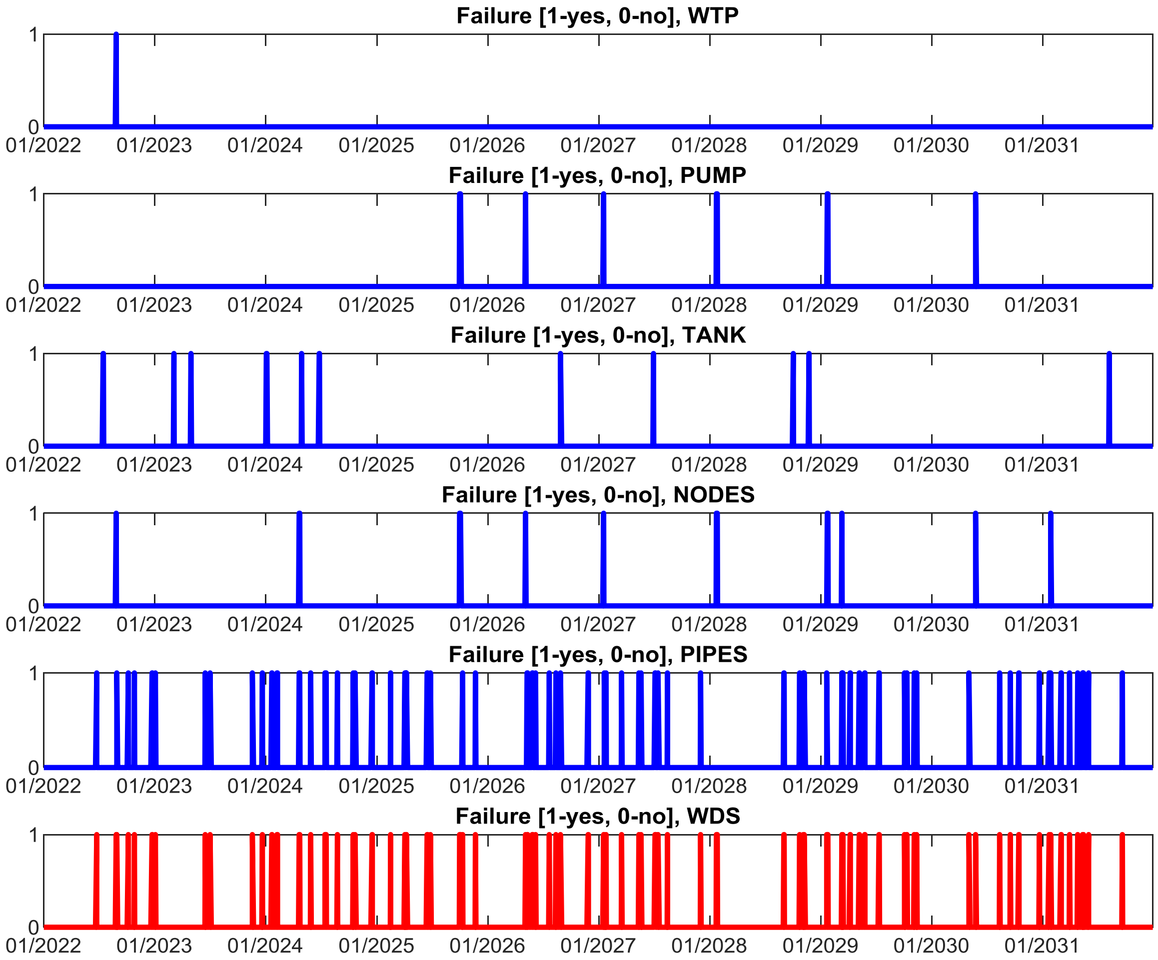

Figure 6 Failures of WDN components. Blue line informs of the failed states of the water treatment plant (WTP), pump (PUMP), water tank (TANK), nodes (NODES), and pipelines (PIPES). Red solid line displays the states of the overall water distribution system (WDS).

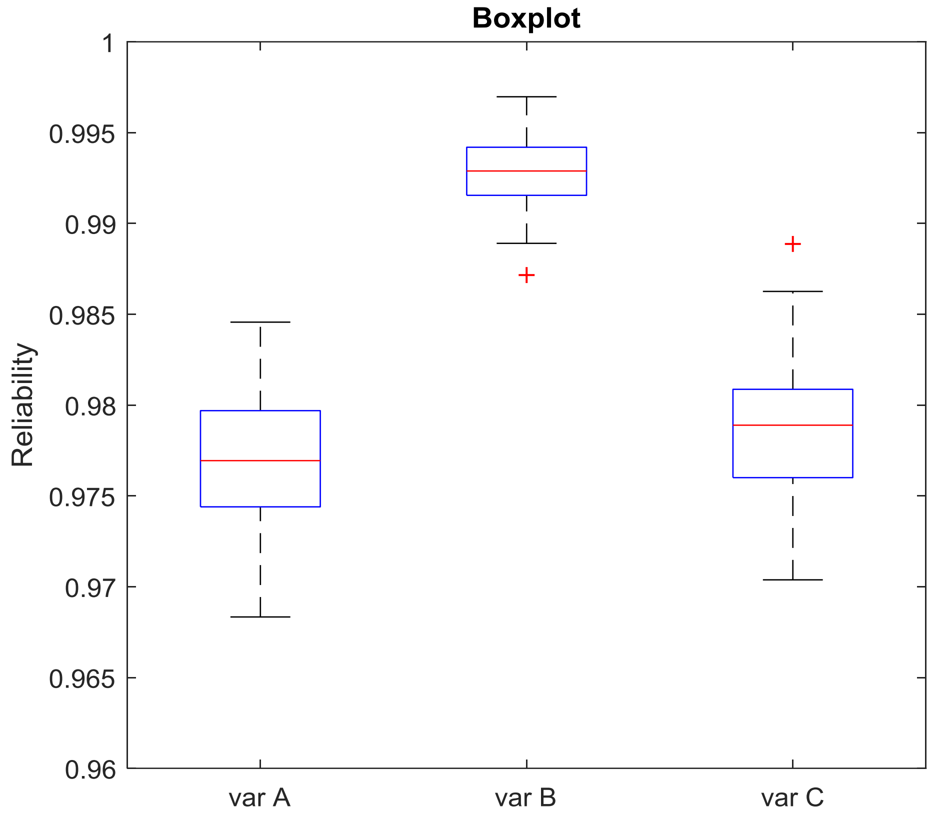

Figure 7 Box plot of Variant A, B and C.

Box plot in Figure 7 compares the reliability Variant A, B and C. The medians are:

Var A: median(R) = 0.9769

Var B: median(R) = 0.9929

Var C: median(R) = 0.9789

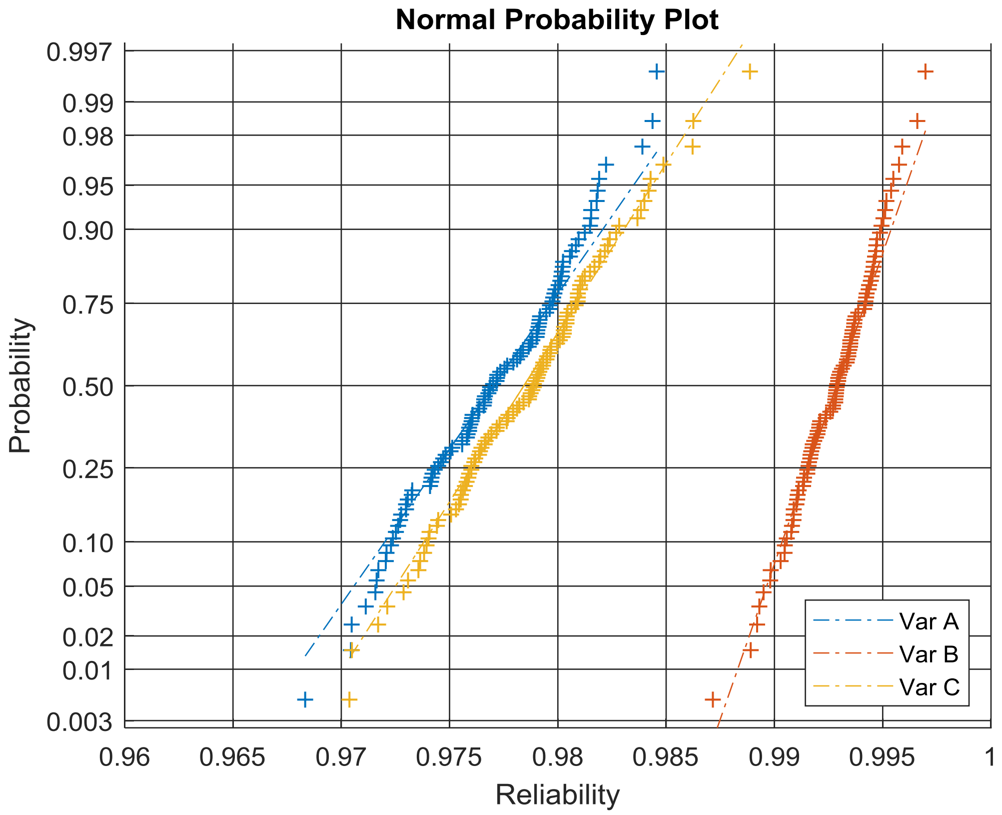

Figure 8 Normal probability plot of reliability for studied variants.

The simulation was first conducted for ten years of operation to obtain the reliability values and then repeatedly (100 runs of ten-year periods) to determine the probability distribution of the system reliability. The application of Monte Carlo simulation aims to evaluate the effect of modernisation/ backup of individual elements on the reliability of the whole WDN. The case study results display how installing a redundant pump, i. e. Variant C affects the system's reliability (compared to the basic scenario, i. e., Variant A). Variant B tests the sensitivity of the WDN overall reliability to pipes reliability by changing the failure rates of pipelines. This change would correspond to pipe modernisation in a real-world context, e. g., by replacement or lining. The simulation results are useable for other objectives (albeit not included in this study), such as cost-benefit analysis (CBA). CBA supports an infrastructure operator's decision-making to select either of the available options, e. g., to either maintain the current network at higher operating costs or invest in a one-off modernisation and expect lower operating costs in the long run. One may solve such an assignment using the Net Present Value method.

Figures 4, 5 and 6 work with Variant A (the basic scenario) and depict the renewal processes of each component of the WDN. The logic of their combination is evident. Here, the Monte Carlo simulation summarises ten years of operation. Figures 7 and 8 present the result of the

Monte Carlo simulation for 100 repeated runs of ten-year periods. These figures look into the probability distribution of the WDN reliabilities for the Variants A, B and C. The analysis shows that the WDN reliability has an approximately normal probability distribution. Figures 7 and 8 compare the impacts of distribution network robustness-enhancing solutions targeting the most sensitive components, i. e. installing a redundant pump or modernising pipelines; this output is relevant for CBA. The relatively minor difference in reliability medians between the considered variants is mostly caused by the small scale of the study network. The variant with the greatest reliability improvement corresponds to piping modernisation (Variant B); such a variant would also be the most expensive in the practical setting.

8 Conclusion

The thesis' focus addresses some of the current issues of the water management structures constituting the drinking water supply sector of critical infrastructures and are acknowledged among the most valuable public assets worldwide. Water supply systems fulfil their function if they meet the requirements set by the population, industry, agriculture, fire rescue service and technical management of municipalities in delivering water in desired quantities and quality. For that reason, a reliable and consistent water supply service under a range of operating conditions (normal and abnormal) is necessary for economic progress, public health, and social well-being.

The research questions were three: (I) What are the current state-of-the-art quantitative methods for risk and reliability analysis of critical infrastructure? (II) For which types of hazards can a state of emergency be reasonably expected to be declared? The research question for the case study is: (III) How reliable is the studied water distribution network and what measures can be taken to enhance its robustness? The works has reached the following conclusions:

Identifying the critical elements of the water supply system is a starting point for risk and reliability analyses, the damage to or whose failure may result in disruption of the supply or deteriorated water quality (research question II). The thesis delineated hazards to water infrastructure both of natural and anthropogenic origin, which may harm the system and contribute to the occurrence of emergencies from synergistic, domino and cascading effects. As shown by the review of hazards, increasing the security of real-world water supply systems necessitates applying a systemic approach for objective analysis of specific conditions. The hazards pertinent for individual components of the water supply chain are compiled in well-known databases *Techneau* and *WaterRisk*.

To solve the research question (I), the thesis examined various methods of reliability and risk assessment for a water distribution system. The designing of water distribution networks has generally been efficiency-oriented – the least-cost design was perused first with implicit considerations for the system reliability, therefore, with vulnerabilities to uncertain future conditions. To date, various performance metrics have been considered to account for the performance of distribution networks in the presence of uncertainty, a source of risk. The reliability belongs to the most extensively employed performance measures and frequently contributes to various risk management considerations. The thesis reviews the matters pertinent to the reliability assessment of water distribution networks whilst solving research question I.

and identifies two categories of reliability methods and considerations – topological and hydraulic. The insight reached with this review informed the solution of a simple study distribution network.

Furthermore, the thesis investigated the development of the critical infrastructure protection (CIP) and water supply protection at the European policy level, formative of the Czech approaches to the protection of critical assets. Recently, CIP has become an important risk management framework for mitigating real and perceived threats to the critical system upon which modern society relies (as outlined, e. g., in Dunn-Cavelty and Suter, 2012). The gradual establishment of risk preparedness in the EU river basin management and the broader water management sectors commenced with the Water Framework Directive 2000/60/EC. Concerning the matter of drinking water supply, the implementation of the amended Directive (EU) 2020/2184 was a substantial change for the water supply providers because it mandated, among other things, the preparation of so-called water safety plans or revisions of rules of operations of water supply infrastructures. The European policy concerning the river basin management and water supply corresponds to the sectors-specific risk management handling of transboundary crises beyond the Member States' capabilities, closely related to the CIP framework considerations.

In the Czech Republic, the risk assessment methods for critical infrastructures were formulated and certified as a part of Directive 2008/114/EC transposition following the general guidelines of the European Commission's DG HOME and DG ECHO. The "*Methodology for Ensuring the Protection of CIs in the Production, Transmission and Distribution of Electricity*" (Deloitte Advisory, 2012) devised a custom semi-quantitative method KARS for European CI designated in the Energy and Transportation sector. It applies to a synergistic and a domino effect of risk propagation, albeit not created for estimating the potential cascading risk effect among other critical infrastructures sectors. A semi-quantitative systemic risk assessment method a semi-quantitative method CIERA proposed by the Technical University of Ostrava supports the resilience approach; it also applies to systemic risk assessment among several CI sectors. Within the water supply sectors, two methodologies were certified. First was prepared by the National Institute of Public Health (2018) as a part of the legislative obligation on risk assessment imposed by the Protection of Public Health Act No. 258/2000 Coll. (following the transposition of the amendment to Council Directive 98/83/EC). This methodology attunes the WHO's proposed method of water safety plans. The second methodology (AF-CITYPLAN et al., 2015) was designed for water supply infrastructure operators to identify the potential systemic risks emanating from the water supply infrastructure failure; handling thereof should be coordinated with crisis management authorities. Both methodologies recommend and outline the FMECA (Failure mode, effects, and criticality analysis) analytical procedure, regularly used in the water management and other engineering sectors.

The thesis shows that formal, structured risk assessment is related to implementing relevant Directives and is yet at the onset in the water supply sector. Furthermore, the Czech domestic procedures involved in risk assessment focused on critical infrastructure and water supply sector harness extensively international expertise and Czech research institutions contribute to its advancement at the European level. To illustrate, the Czech Republic (namely the infrastructure operators, Fire Rescue Service, Ministry of Interior, Ministry of Industry and Trade, and Transportation) takes part in the EU platform specialised in expertise-sharing via the expert groups of EPCIP, ERNCIP and CIWIN. The National Institute of Public Health participated in the European research project *Techneau* within the FP6 framework for detecting hazards to the water supply sector. Further, the Institute of Municipal Water Management (IMWM) of the Faculty of Civil Engineering, Brno University of Technology, contributed to the international C19 Proactive crisis management of urban infrastructure organised by European Cooperation in Science and Technology (COST). The Technical University of Ostrava is engaged in the methodological research of resilience approaches to critical infrastructures supported by the EU.

Per research question III., the thesis elaborated on some of the merits and limitations of FMECA and, on that basis, tested the stochastic simulation method, Monte Carlo, to evaluate the systemic reliability (both mechanical and hydraulic properties) of a study of the water distribution network (as a whole) and identify its sensitive elements in three scenarios. The simulation methods revealed their benefits for potential cost-benefit analysis because they allow straightforward relative ranking of alternative variants of robustness-enhancing options and, therefore, contribute to risk management.

Summary

- The thesis entitled “*Security Risks for Critical Infrastructures in Water Management Sector*” addresses some of the current issues connected with the risk and reliability assessment of hydraulic structures comprising the drinking water supply system. The objective of the thesis was to examine the current state of the implementation of systemic risk assessment of the water supply chain in the Czech Republic.
- The thesis posed two research questions to solve the mentioned objective. First, the inquiry focused on the current state-of-the-art risk and reliability analysis methods for general critical infrastructures as networked systems and then specifically for water supply. As a part of addressing this question, the thesis looks into the contemporary principles of the critical infrastructure protection framework and the corresponding policy debate and Directives leading to the gradual establishment of risk preparedness in the river basin management at the European Union level, which has been formative of the critical infrastructure protection in the Czech Republic and set out obligations for conducting regular risk assessment in the selected areas of water management, namely the of the flood hazards, hazards to ECI (namely, waterways and navigation), and newly also the drinking water system per the recently amended Directive (EU) 2020/2184. The thesis introduces the recommended risk analytical method used by the Czech water management industry experts and the administration sector and highlights its merits and limitations.
- Second, the thesis surveys for which the types of hazards, both natural and anthropogenic, can a state of emergency be reasonably expected to be declared. The text focuses on systemic risk and reliability; therefore, it investigates the modes of risk capacitated and propagated by various interdependencies within the networked infrastructures system. Considering the water supply chain as a dynamic system and accounting for its systemic dependencies and behaviour is the necessary task for risk and reliability evaluation to be integrated into the risk considerations in Czech water management.
- The third research question was solved as a part of a reliability assessment of a simple study distribution network. The case study was carried out based on the knowledge gained from the overview of the current state of reliability assessment methods for water distribution networks and tests the Monte Carlo simulation for modelling random failures in the network and its benefits for risk management and ranking and comparison of selected network robustness-enhancing options.

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