


Review

Water Supply in the Czech Republic: Review of Infrastructure Risks and Comparison with Worldwide Practices

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Abstract

Water distribution systems (WDSs) are vital components of public infrastructure, ensuring the safe supply of drinking water. However, they are increasingly exposed to technical failures, contamination events, natural disasters, and cyberattacks. This review analyses global risks to water distribution systems (WDSs), focusing on biological, chemical, and cyber threats, and compares international approaches to detection, monitoring, and crisis management. Special attention is given to advanced technologies, such as sensors, digital modelling, and innovative disinfection methods, that enhance resilience and enable rapid contamination response. Case-based insights from the Czech Republic illustrate the strengths of a system with consistently high water quality standards while also revealing vulnerabilities linked to ageing infrastructure, limited digitalisation, and emerging risks related to climate change and cybersecurity. The review further highlights differences in international hygiene standards and regulatory frameworks and their implications for water safety. Future research priorities include: (I) predictive modelling and machine learning for contamination dynamics; (II) advanced disinfection combining UV, ozone, and nanomaterials; (III) systematic study of biofilms and microbial resistance; (IV) monitoring and risk assessment of pharmaceuticals, PFASs, and other emerging contaminants; (V) development of rapid, low-cost sensors and biosensors for real-time detection; and (VI) socio-technical studies addressing risk communication and public trust in drinking-water systems. Recommendations focus on systematic infrastructure renewal, enhanced monitoring and predictive modelling, and stronger integration of crisis preparedness and cybersecurity. Overall, the results underline the need for sustained investment, technological innovation, and cross-sector cooperation to ensure long-term water security.

Keywords: water distribution systems (WDSs); drinking-water safety; contamination detection; infrastructure security; biological and chemical risks; cybersecurity; case study; Czech Republic; crisis preparedness; water quality monitoring; resilience



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1. Introduction

Water distribution systems form the backbone of modern civilization, providing universal access to safe drinking water—an essential resource for health, economic stability, and societal well-being. Globally, they are increasingly challenged by ageing infrastructure, contamination incidents, extreme weather events, and emerging cyber threats [1–12]. These risks affect not only developing countries, where over two billion people still lack safe drinking water, but also advanced economies, where failures linked to technical breakdowns, sabotage, or insufficient maintenance have been repeatedly documented [2,11–16].

In this review, the term drinking-water systems is used as an umbrella concept encompassing water sources, treatment, and distribution; water supply systems refer to the technical and organisational provision of water services; water distribution systems (WDSs) denote the infrastructure responsible for transporting treated water to consumers; and water distribution network is used specifically to describe the topological structure of pipes, nodes, and links within the distribution system.

Ensuring a safe and resilient water supply has thus become a central focus of international policy and research. Organisations such as the World Health Organization (WHO), the European Commission (EC), and the U.S. Environmental Protection Agency (EPA) regularly update water quality standards, disinfection requirements, and crisis management guidelines [2,17–19]. Global trends increasingly emphasise digitalisation, predictive modelling, and advanced sensors that enable rapid detection of contamination and more effective emergency management [1,7,20–30].

Within this international context, the Czech Republic represents a valuable case study. Although drinking-water quality in the country is generally high by European standards, it faces structural and technological challenges comparable to those observed in other developed states [31–37]. These include ageing infrastructure, fragmented ownership and financing, and limited adoption of digital technologies [38]. At the same time, climate change is expected to intensify hydrological stress, while the rising frequency of cyberattacks on critical infrastructure exposes vulnerabilities of increasingly digitalised systems [35,36,39–47]. The Czech Republic is used not merely as a descriptive national example but as an analytical lens, representing a highly regulated and technically mature European water sector facing structural fragmentation and digital transition pressures.

The Czech water sector, therefore, illustrates a paradox: strong historical and regulatory foundations coexist with emerging risks that require new tools and strategies. By combining a global review of contamination risks and protection measures with case-based insights from the Czech Republic, this study highlights both shared challenges and region-specific vulnerabilities. It further aims to identify policy and research priorities to strengthen long-term resilience and water security.

Existing review studies addressing the safety and resilience of water distribution systems have predominantly followed two main lines of inquiry. First, many reviews examine individual categories of risk in isolation, such as biological contamination, chemical micropollutants, or cybersecurity incidents. Second, other studies focus primarily on detection and monitoring technologies, often without explicitly embedding these tools within broader frameworks of risk management, crisis preparedness, and institutional governance. Consequently, the current literature provides only a limited integrative perspective on how biological, chemical, and cyber-physical risks interact within complex water distribution systems and how these interactions influence operational resilience. To date, no review has systematically integrated biological, chemical, and cyber-physical risks within a unified multi-barrier and governance-oriented framework that explicitly addresses their interaction and implications for operational resilience.

This review seeks to address this gap by offering an integrated synthesis that systematically links multiple risk domains with multi-barrier protection concepts, monitoring strategies, governance arrangements, and their practical implications for system operation. These global insights are contextualised through a focused case study of the Czech Republic, which represents a mature and highly regulated water supply system characterised by consistently high drinking-water quality, yet also by institutional fragmentation and increasing exposure to technological, environmental, and cyber-related challenges. As such, the Czech case provides transferable insights relevant to other advanced water

systems facing comparable structural fragmentation, ageing infrastructure, and digital transition pressures.

On this basis, the review is guided by the following research questions:

Q1: What are the dominant biological, chemical, and cyber-physical threats affecting water distribution systems, and in what ways can these threats interact to produce complex risk scenarios?

Q2: Which monitoring, detection, disinfection, and digital approaches have been reported as effective in international practice for the early identification and management of contamination and disruption events?

Q3: What specific strengths and vulnerabilities characterise the Czech water sector, and what priorities emerge from this analysis for policy development, investment strategies, and future research?

The conceptual framework of this review classifies risks affecting water distribution systems into biological, chemical, and cyber-physical categories and addresses their management through a multi-barrier protection approach spanning source water, treatment, distribution networks, and operational control. The global review component is used to identify recurring risk patterns and effective countermeasures across international contexts, while the Czech case study serves as an analytical lens to examine the transferability of these insights to a Central European water sector characterised by fragmented ownership and operational arrangements. Accordingly, the manuscript first outlines the state and institutional characteristics of Czech water infrastructure, then compares international standards and prevailing risk trends, and finally synthesises the implications in the discussion, research priorities, and policy-relevant recommendations.

2. Materials and Methods (Methods of Review)

This review was based on an extensive analysis of the scientific literature and technical reports addressing the risks, monitoring technologies, and resilience of drinking-water WDSs.

The literature search covered the period 1994–2025, focusing on recent advances in digitalisation, contamination detection, and cybersecurity. Sources were retrieved mainly from ScienceDirect, Google Scholar, and institutional publications of the WHO, the EC, and the EPA.

For the national context, relevant Czech sources were included, such as reports from the Czech Hydrometeorological Institute (CHMI), the National Institute of Public Health (SZÚ), and the Ministry of Agriculture (MZe). Studies were selected based on their direct relevance to drinking-water safety, infrastructure protection, and crisis management.

The review followed a qualitative synthesis approach, combining international findings with case-based insights from the Czech Republic. Particular attention was given to (I) contamination types (biological, chemical), (II) cyber-physical threats and their physical consequences, (III) detection and monitoring technologies, and (IV) policy and governance frameworks.

Each source was evaluated for methodological robustness, geographic coverage, and applicability to Czech conditions.

Findings were subsequently structured into thematic sections aligned with the conceptual framework introduced in the Introduction, reflecting:

1. The current state and structural characteristics of drinking-water infrastructure in the Czech Republic, with particular emphasis on WDSs;
2. A comparative analysis of international regulatory frameworks, standards, and risk profiles affecting drinking-water safety;

3. Lessons learned from selected international and Czech case studies addressing contamination events, cyberattacks, and system failures;
4. The identification of key research gaps and policy-relevant recommendations related to monitoring, digitalisation, governance, and system resilience.

This integrative design ensured a balanced comparison of national and global perspectives and provided the analytical foundation for the discussion and recommendations presented in later sections.

The Literature Search and Screening Process

The literature search was conducted following a structured, PRISMA-inspired approach in order to enhance methodological transparency and reproducibility while recognising the narrative and contextual nature of the review. Searches were performed in the scientific databases Scopus, Web of Science, and PubMed, supplemented by Google Scholar and ScienceDirect. In addition, key institutional and policy documents were retrieved from international organisations, including the WHO, the EC, and the EPA, as well as from relevant Czech national institutions (SZÚ, MZe, CHMI, NCIB, and SOVAK ČR).

The search covered publications from 1994 to 2025 and was limited to sources published in English and Czech. The literature search was finalised on 26 December 2025, which represents the reference point for the regulatory frameworks, technologies, and threat landscapes discussed in this review.

Exemplary search strings included combinations such as: (“water distribution system” OR WDS OR “drinking water network”) AND (contamination OR “emerging contaminants” OR pharmaceuticals OR PFAS OR biofilm) AND (monitoring OR sensor* OR “early warning” OR detection); and, in parallel, (“water utility” OR SCADA OR ICS) AND (cyberattack OR cybersecurity OR “cyber-physical”).

Inclusion criteria comprised: (I) direct relevance to risks affecting water distribution systems (biological, chemical, or cyber-physical); (II) a focus on detection, monitoring, disinfection, or incident management; and (III) studies providing empirical evidence, case studies, methodological approaches, or authoritative guidelines.

Exclusion criteria included: (I) studies unrelated to drinking water or water distribution systems (e.g., wastewater-only studies); (II) purely laboratory-based research without implications for WDS operation; (III) duplicate records; and (IV) sources without accessible full text. A structured overview of the search strategy, including databases, scope, and inclusion and exclusion criteria, is provided in Table 1.

Table 1. Summary of the PRISMA-inspired literature search strategy used in this review, including databases, search scope, inclusion and exclusion criteria, and the definitive literature cut-off date.

| Element | Description |
|---------------------------|---|
| Databases | Scopus, Web of Science, PubMed, Google Scholar, ScienceDirect |
| Institutional sources | WHO, EC, EPA, SZÚ, MZe, CHMI, NÚKIB/NCIB, SOVAK ČR |
| Time span | 1994–2025 |
| Languages | English, Czech |
| Document types | Peer-reviewed articles, reports, guidelines |
| Search strings (examples) | WDS AND contamination; PFAS AND drinking water; SCADA AND cybersecurity |

Table 1. *Cont.*

| Element | Description |
|--------------------|--|
| Inclusion criteria | Relevance to WDS risks; monitoring/detection/incident management; empirical or guideline-based |
| Exclusion criteria | Wastewater; lab-only; no full text |
| Cut-off date | 26 December 2025 |

In total, 261 records were identified in the initial search. Following title and abstract screening, 105 records were excluded, and 156 full-text articles and reports were retained for qualitative synthesis. Each source was evaluated with respect to methodological robustness, geographical relevance, and applicability to Czech conditions.

This review is explicitly designed as a qualitative, contextual synthesis rather than a formal systematic review. Consequently, no quantitative meta-analysis or formal risk-of-bias assessment was conducted. Quantitative risk assessment and economic modelling are therefore beyond the scope of this study and are identified as priority directions for future research.

3. Overview—Water Infrastructure in the Czech Republic

3.1. Performance Indicators and Network Vulnerability

The Czech Republic, a landlocked Central European country (78,866 km²; 10.9 million inhabitants) [33–36], lies on the main European watershed dividing the basins of the North, Baltic, and Black Seas. Most major rivers (Vltava, Elbe, Morava, Dyje, and Odra) originate within its territory, which makes national water resources highly dependent on precipitation and reservoir storage [35,36,48]. Renewable water resources reach about 1450 m³ per capita, slightly above the European average. Drinking water is obtained almost equally from surface and groundwater sources, 51% vs. 49% in 2021, ensuring good resilience during droughts [35,36]. Groundwater is mainly supplied from wells and springs and generally requires minimal treatment, while surface water from rivers and reservoirs undergoes more extensive purification [49]. In total, more than 4000 water supply sources are distributed across the country [35,50]. The spatial distribution of groundwater abstraction points (shallow and deep wells) and springs is shown in Figure 1.

The organisation of the Czech water sector reflects post-1990 decentralisation: ownership of water and sewerage assets was transferred to municipalities, resulting in a fragmented structure of approximately 7900 owners and 3000 operators managing over 81,000 km of pipelines and 4210 treatment plants [35,38,43]. Although 96% of inhabitants are now connected to public supplies and distribution losses have fallen to 14.8%, small municipalities often lack funds for systematic renewal [45,46].

Operational performance indicators (KPIs), such as network extent, water losses, pipe age, and failure frequency, should not be understood merely as descriptive technical parameters but as structural determinants of the risk profile of water distribution systems. Elevated failure rates and insufficient renewal levels increase the likelihood of pressure drops and contaminant intrusion, thereby reinforcing the importance of early-detection mechanisms and operational barriers, including pressure management, systematic flushing, and effective residual disinfection. At the same time, institutional fragmentation constrains data standardisation, information sharing, and coordinated crisis response across utilities. This disparity contributes to uneven preparedness levels within the sector, particularly among smaller operators, and further underscores the need to integrate infrastructure

performance, governance capacity, and risk management strategies within a coherent resilience framework.



Figure 1. Geographical distribution of groundwater supply sources in the Czech Republic (shallow wells, deep wells, and springs), illustrating regional patterns in groundwater abstraction [50].

For several key performance indicators (KPIs), data are not collected and reported in a harmonised manner; these include failure frequency, systematic records of pressure drops, and standardised statistics on water quality incidents. The availability and quality of these data vary across utilities, limiting comparability and constraining targeted risk management. Establishing minimum standards for the collection, reporting, and sharing of operational data across the sector would likely represent an important step toward improving transparency, benchmarking, and resilience-oriented decision-making. Selected KPIs aligned with the IWA performance indicators framework and their relevance for risk management are summarised in Table 2.

Table 2. Selected key performance indicators (KPIs) aligned with the IWA performance indicators (PIs) framework for water distribution systems: definition, risk relevance, and indicative data availability in the Czech Republic.

| KPI (IWA PI Code; Unit) | Short Definition (As Used in Practice) | Why it Matters for Risk | Data Availability (CZ) |
|---|---|--|------------------------|
| QS9; %—Pressure of supply adequacy (%) | Share of service connections/delivery points meeting the target pressure (typically assessed at peak demand hour) | Low/unstable pressure increases intrusion risk and degrades service reliability | Low–Medium |
| QS12; No./1000 connections—Interruptions per connection | Total number of supply interruptions/number of service connections × 1000 (annual) | Captures customer impact of outages; supports benchmarking of operational resilience | Medium |
| QS17; %—Microbiological (%) | Share of compliant microbiological tests (annual) | Direct public-health safety outcome indicator | High |

Table 2. Cont.

| KPI (IWA PI Code; Unit) | Short Definition (As Used in Practice) | Why it Matters for Risk | Data Availability (CZ) |
|--|--|---|--|
| QS18; %—Physical-chemical (%) | Share of compliant physical-chemical tests (annual) | Captures chemical compliance and longer-term quality issues | High |
| Op17; %/year—Replaced or renewed mains (%/year) | Length of mains replaced/renewed during the year/total mains length $\times 100$ | Low renewal rate accelerates ageing, failures, and vulnerability | Medium |
| Op22; m ³ /connection/year—Water losses (m ³ /connection/year) | Total water losses per service connection per year | Core leakage/efficiency KPIs indirectly relates to the infrastructure condition | Medium |
| Op25; dimensionless—Infrastructure leakage index (ILI) | Ratio-type leakage benchmark (ILI) | Standard IWA benchmark for leakage management and prioritising interventions | Low (computed by a subset of larger utilities; not harmonised or routinely reported sector-wide) |
| Op26; No./100 km/year—Mains failures | Number of mains failures per 100 km per year | Direct condition KPI; failures trigger pressure transients and contamination pathways | Low–Medium |

Note: “KPI” is used here as a generic term; indicator names, units, and codes follow the IWA PI framework.

In this paper, the term key performance indicators (KPIs) is used as an umbrella term for performance metrics aligned with the IWA performance indicators (PIs) framework (QS for quality of service; Op for operational indicators).

Drinking-water quality in the Czech Republic demonstrates consistently high compliance, with long-term monitoring confirming >98% compliance with hygienic standards [31–33,37]. Quality control is ensured by operators in cooperation with regional health authorities under legislation harmonised with EU Directive 2020/2184 [51–54]. Residual disinfection relies mainly on chlorination, occasionally supplemented by ozone or UV treatment [33,55]. Recent surveys by the SZÚ detected trace pharmaceutical residues in several raw-water sources [56], leading to proposed monitoring limits for 2024 ($\leq 0.1 \mu\text{g/L}$ per compound; $\leq 0.5 \mu\text{g/L}$ total) [57]. Attention is also shifting to PFASs, which are not yet regulated nationally but are under discussion in the EU and USA [58,59].

Since the early 1990s, infrastructure security and crisis preparedness have been partly delegated to utilities. Larger operators occasionally participate in exercises coordinated by the Fire Rescue Service, while smaller ones lack the capacity for regular training [47,60–62]. Traditional scenarios focus on floods or chemical accidents, but cyberattacks and deliberate contamination remain insufficiently addressed [36,56,57,63–67].

Preparedness levels vary considerably according to the size and institutional capacity of the utility. Large water companies typically maintain specialised expertise in crisis planning, IT/OT security, and structured cooperation with emergency response services, enabling more frequent exercises and the implementation of standardised procedures. Medium-sized utilities often possess partial capacities; however, they face financial and staffing constraints, particularly in relation to cyber-physical risk scenarios. Small and municipal operators frequently operate with minimal personnel reserves and without systematic training frameworks, resulting in limited preparedness and predominantly reactive crisis management [2,7,16,18,19]. This uneven distribution of institutional capacity contributes to sector-wide disparities in resilience and underscores the need for shared

methodologies, strengthened regional cooperation, and clearly defined minimum standards to ensure a baseline level of crisis preparedness across all operator categories.

The legal framework combines public health, water management, and crisis legislation. The cornerstone is Act No. 258/2000 Coll. on Public Health Protection, supplemented by Decree No. 252/2004 Coll. (amended 371/2023 Coll.) in harmony with EU requirements [51–54,61,62]. Technical standards (ČSN 75 5201) define treatment design, while Acts No. 110/1998 and 240/2000 regulate crisis management and critical-infrastructure protection [62,68].

3.2. Interpretation of Water Source Distribution and Regional Vulnerability

The spatial distribution of surface water and groundwater sources leads to regionally differentiated exposure to drought and contamination risks. Systems relying predominantly on surface water are more vulnerable to episodic water quality degradation driven by hydrological extremes and diffuse pollution, necessitating robust treatment barriers and intensified raw water monitoring. In contrast, groundwater-dependent regions generally exhibit greater short-term quality stability but face long-term vulnerabilities related to persistent micropollutants and localised contamination sources. These patterns underscore the need for differentiated resilience planning tailored to source type and local vulnerability.

3.3. Strategic Assessment of the Czech Water Distribution System (SWOT Analysis)

Overall, the Czech system combines high-quality resources, strong regulation, and dense infrastructure, yet faces persistent weaknesses: ageing pipelines, limited digitalisation, fragmented ownership, and emerging threats, such as pharmaceuticals, PFASs, and cyber risks [32,33,37–39,41,44,45,47,49,56,57,69]. To sustain current standards, priorities should include systematic renewal, IoT-based monitoring, enhanced cybersecurity, and unified investment planning [39–42,44,70–73]. This paragraph summarises a SWOT analysis of the Czech WDS, which is presented in detail in Table 3 below, highlighting strengths, weaknesses, opportunities, and threats specific to the country. The SWOT assessment is based on a synthesis of the literature reviewed in Sections 2 and 3 and reflects structural patterns consistently identified across national and international sources.

Table 3. SWOT analysis of drinking WDSs in the Czech Republic (source: author’s own elaboration).

| S—Strengths | W—Weaknesses |
|---|--|
| High population coverage by public water supply systems. | Ageing infrastructure and a low renewal rate of certain pipeline sections (higher failure rates, pressure anomalies). |
| Long-term high compliance with hygienic limits (stable drinking-water quality). | Fragmented ownership and operation (more difficult coordination of investments, standards, and crisis procedures). |
| Regulation harmonised with EU legislation and an established system of sanitary monitoring and supervision. | Non-uniform database (KPIs, failure records, pressure drops, incidents) and limited interoperability between entities. |
| Experience in managing traditional crisis situations (floods, accidents, supply interruptions). | Uneven level of digitalisation and online monitoring (often limited to outside main facilities and smaller systems). |
| Existing professional and institutional capacity within the sector (methodologies, knowledge sharing). | Uneven preparedness (especially among smaller operators: staffing capacity, cyber-OT security, emergency exercises). |

Table 3. Cont.

| O—Opportunities | T—Threats |
|---|---|
| Targeted risk-based investments in network renewal (risk-based asset management)—greater impact on safety and resilience. | Climate extremes (droughts and floods) are increasing operational stress and fluctuations in raw water quality. |
| Expansion of online monitoring and anomaly detection (IoT, early warning, integration of hydraulic data). | Emerging contaminants (e.g., PFASs, pharmaceuticals) and the resulting demand for new treatment technologies and monitoring approaches. |
| Introduction of minimum data standards and sector-wide KPI sharing (improved comparability and risk management). | Cyberattacks targeting IT/OT systems (SCADA) and the risk of operational manipulation (dosing, valves, pressure regimes). |
| Shared services and regional cooperation (joint audits, exercises, cyber capacities, laboratories). | Energy and investment pressures (rising OPEX/CAPEX) are leading to deferred renewal and increased vulnerability. |
| Utilisation of national/EU programmes for modernisation, digitalisation, and cybersecurity enhancement. | Workforce capacity constraints and ageing expertise (shortage of qualified personnel for operation and security). |

The following SWOT analysis summarises the strengths and vulnerabilities of the Czech water supply system in a manner intended to support practical application, particularly in investment prioritisation, monitoring strategies, and crisis preparedness. Emphasis is placed on measurability and the direct linkage of each factor to operational risk.

Two identified weaknesses within the SWOT analysis have direct operational implications for incident management. First, the combination of ageing infrastructure and insufficient renewal rates increases failure frequency and, consequently, the probability of secondary contamination events. This structural condition translates into heightened demands on pressure management, systematic flushing programmes, and the rapid localisation of anomalies within the network. Second, limited digitalisation and insufficient data interoperability constrain early-detection capacity and coordinated response across utilities. In the absence of harmonised data standards and a minimum baseline of online monitoring, crisis management, particularly among smaller operators, remains predominantly reactive rather than preventive.

4. Global Comparison of Problems and Trends

Drinking WDSs across the world face a universal set of risks that challenge their safety, reliability, and resilience [17,74–76]. Ageing infrastructure, water losses, contamination events, extreme weather, and cyberattacks increasingly affect even highly developed systems [3–10,23,29,77–80]. These issues have prompted international organisations, such as the WHO, the EC, and the EPA, to strengthen water safety standards, disinfection requirements, and crisis-management frameworks [2,19,59]. Current global trends emphasise digitalisation, predictive modelling, and advanced sensor technologies that enable faster detection of contamination and more effective emergency response [1,3,7,17,20,22,25,26,29,30,81–89]. Within this context, the Czech Republic provides a relevant case study illustrating how a system with high regulatory standards must now adapt to emerging technological and environmental challenges shared worldwide.

4.1. International Standards—Similarities and Differences

Although global frameworks for drinking-water safety pursue similar objectives, important regulatory differences persist among jurisdictions [2,18,19]. The European Union (EU) and the Czech Republic apply the precautionary principle, maintaining relatively strict

thresholds such as nitrates at 50 mg/L, pesticides at ≤ 0.1 $\mu\text{g/L}$ per compound (0.5 $\mu\text{g/L}$ total), and radon at 300 Bq/L to ensure high consumer protection (Directive 2020/2184 EU; Decree 371/2023 Coll.) [2,18,19,51–54].

Among emerging contaminants of increasing regulatory and scientific concern are per- and polyfluoroalkyl substances (PFASs), a broad group of synthetic fluorinated compounds that have been widely used in industrial applications and consumer products due to their exceptional chemical stability and resistance to degradation. These substances are characterised by high environmental persistence, potential for long-range transport, and bioaccumulation in both ecosystems and the human body, which has led to their designation as so-called “forever chemicals” [58,59,90,91]. In recent years, alongside other emerging contaminants, PFASs have received growing attention because of their widespread occurrence in drinking-water sources and mounting evidence of adverse health effects [90,91]. In particular, perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) have been extensively investigated due to their historical use in firefighting foams, surface treatments, and chemical manufacturing. Epidemiological and toxicological studies have linked exposure to these compounds to immunotoxicity, endocrine disruption, developmental effects, and increased cancer risk, even at very low concentrations [58,59,90–94]. In this review, pharmaceuticals refer to pharmaceutically active compounds detected as trace micropollutants in raw and/or drinking water (e.g., antibiotics, analgesics, hormones).

The WHO adopts health-based guidelines that balance safety with feasibility in low-resource settings, e.g., nitrites 3 mg/L, fluoride 1.5 mg/L, and no specific limit for radon [2]. The EPA, by contrast, has introduced the most stringent limits for emerging contaminants, particularly PFASs, with new maximum contaminant levels of 0.004 $\mu\text{g/L}$ for PFOA and PFOS [19].

These variations reflect differences in policy priorities, technological capacity, and socio-economic context, and they complicate international harmonisation. Nevertheless, the general convergence of standards in microbiological and heavy-metal indicators demonstrates progress toward shared global safety objectives [2,19,95]. For future alignment, cooperation between the WHO, EU, and EPA frameworks will be essential, especially for newly regulated substances such as pharmaceuticals, PFASs, and endocrine disruptors [2,19,90–93]. Table 4 summarises a comparison of selected parameter limits between the Czech Republic, the WHO, and the EPA [2,18,31,37,45,49–54,59].

Table 4. Comparison of selected drinking-water parameters. All values are valid in 2025. Sources: Czech Decree No. 371/2023 Coll. [53]; WHO Guidelines for Drinking-water Quality, 4th edition [58]; EPA National Primary Drinking-Water Regulations [59]. Note: Some values are expressed differently (e.g., nitrates/nitrites as nitrogen content in EPA), and conversions are indicated in parentheses [2,18,31,37,45,49–54].

| Parameters | Limit Czech Republic | Limit WHO | Limit EPA |
|------------------------------|---------------------------------|---|---|
| Nitrates (NO_3^-) | 50 mg/L | 50 mg/L | 10 mg/L as N (≈ 45 mg/L NO_3^-) |
| Nitrites (NO_2^-) | 0.5 mg/L | 3 mg/L | 1 mg/L as N (≈ 3.3 mg/L NO_2^-) |
| Lead (Pb) | 5 $\mu\text{g/L}$ | 10 $\mu\text{g/L}$ | 15 $\mu\text{g/L}$ (Action Level) |
| PFASs | Total PFAS: 0.1 $\mu\text{g/L}$ | Total PFAS: 0.5 $\mu\text{g/L}$; PFOA: 0.1 $\mu\text{g/L}$; PFOS: 0.1 $\mu\text{g/L}$ | PFOA: 0.004 $\mu\text{g/L}$ = 4 ng/L; PFOS: 0.004 $\mu\text{g/L}$ = 4 ng/L; PFNA: 0.01 $\mu\text{g/L}$ = 10 ng/L; PFHxS: 0.010 $\mu\text{g/L}$ = 10 ng/L |
| Radon (Rn) | 300 Bq/L | 100 Bq/L | Proposed: 4000 pCi/L (~ 148 Bq/L) |

Table 4. Cont.

| Parameters | Limit Czech Republic | Limit WHO | Limit EPA |
|--|--|--|--|
| Trichloromethane (Chloroform) | 30 µg/L | 300 µg/L | 80 µg/L |
| Fluorides (F ⁻) | 1.5 mg/L | 1.5 mg/L | Maximum contaminant level (MCL): 4.0 mg/L; secondary (aesthetic) standard (SMCL): 2.0 mg/L |
| Chlorite (ClO ₂ ⁻) | 250 µg/L = 0.25 mg/L | 0.7 mg/L | Maximum contaminant level (MCL): 1.0 mg/L; maximum contaminant level goal (MCLG): 0.8 mg/L |
| Manganese (Mn) | 0.05 mg/L | 0.4 mg/L | 0.1 mg/L (long-term); 0.3 mg/L (short-term) |
| Iron (Fe) | 0.2 mg/L | 0.3 mg/L | 0.3 mg/L |
| Selenium (Se) | 20 µg/L | 40 µg/L | 50 µg/L |
| Uranium (U) | 15 µg/L | 30 µg/L | 30 µg/L |
| Pesticides | Individual pesticide: 0.1 µg/L; total pesticides: 0.5 µg/L | Individual limits for each pesticide | Individual limits for each pesticide |
| Chlorine (Cl ²) | 0.3 mg/L | 5 mg/L | 4 mg/L |
| Sulphates (SO ₄ ²⁻) | 250 mg/L | No specific limit. Above 500 mg/L laxative effect | 250 mg/L; above 500 mg/L laxative effect |
| Mercury (Hg) | 1 µg/L | 6 µg/L | 2 µg/L |
| Cadmium (Cd) | 5 µg/L | 3 µg/L | 5 µg/L |
| Aluminium (Al) | 0.2 mg/L | Operational target: <0.1 mg/L (with coagulation), <0.2 mg/L otherwise) | 0.05–0.2 mg/L |
| Cyanides (CN ⁻) | 0.05 mg/L = 50 µg/L | 70 µg/L (long-term); 500 µg/L (short-term) | 200 µg/L |
| Benzene | 1 µg/L | 10 µg/L | 5 µg/L |
| Microorganisms (<i>Cryptosporidium</i> , <i>E. coli</i> , <i>Legionella</i> , <i>Enterococci</i> , <i>Coliform bacteria</i>) | No tolerance | No tolerance | No tolerance |

Note: All drinking-water limits in this table are valid as of 2025, although the underlying standards and guidelines were established in different years, Czech Decree No. 371/2023 Coll.; WHO Guidelines for Drinking-water Quality, 4th edition, 2022; EPA National Primary Drinking-Water Regulations, first enforceable PFAS rule finalised in 2024 [53,58,59]. For PFASs, regulations vary in approach: the Czech limit applies to total PFAS (sum of selected PFASs), WHO guidelines include both a total PFAS framework and substance-specific guideline considerations, and the EPA sets individual Maximum Contaminant Levels (MCLs) for specific PFAS compounds rather than a single total PFAS limit. Conversion notes (e.g., EPA nitrogen basis) are shown in parentheses where applicable.

The implications of regulatory differences among the Czech framework, the WHO, and the EPA can be synthesised across four main domains. First, microbiological indicators exhibit broad convergence around a “zero-tolerance” principle. Second, traditional chemical parameters reveal notable divergence, particularly in the WHO approach, which places greater emphasis on feasibility and context-specific risk management. Third, emerging contaminants, most prominently PFASs and pharmaceuticals, illustrate a clear regulatory

shift toward more stringent and substance-specific limit values, most pronounced in the EPA framework. Fourth, differences are also evident in operational parameters related to disinfection practices and their verification [2,18,31,37,45,49–54].

From a risk management perspective, these regulatory patterns imply that jurisdictions adopting stricter limits for emerging contaminants must invest in more sensitive monitoring systems and advanced treatment technologies, such as adsorption processes, ozonation, or multi-barrier treatment combinations. Conversely, regulatory environments based on more general guideline values allow greater interpretative flexibility, which may result in uneven implementation across utilities. In the Czech context, these differences underscore the priority of progressively expanding monitoring programmes for emerging contaminants while aligning regulatory ambitions with the realistic investment capacities of water utilities.

4.2. Shared Global Challenges

Despite major differences in geography and governance, WDSs worldwide face a recurring set of challenges that threaten both water quality and service reliability [3,16]. These issues are increasingly interlinked; technical, environmental, and digital risks combine to create complex, cross-sector vulnerabilities [3–5,38,89].

- (1) **Ageing Infrastructure.**
In many industrialised countries, a large share of WDSs was constructed before 1980, and renewal rates remain below 1% per year. Leaks, pressure losses, and pipe failures increase the risk of secondary contamination.
- (2) **Climate Change and Extreme Events.**
Floods, droughts, and temperature fluctuations place additional stress on water supply systems, affecting both the quantity and the quality of available water.
- (3) **Emerging Contaminants.**
Pharmaceuticals, PFASs, pesticides, and microplastics persist through conventional treatment and remain inconsistently regulated across countries.
- (4) **Direct Cyber-Physical Threats.**
Attacks targeting SCADA/OT systems can directly disrupt physical operations, including chemical dosing, pressure control, and pumping, potentially leading to contamination or operational incidents. Effective mitigation requires OT-specific incident response procedures, integration with multi-barrier protection strategies, rapid system isolation or transition to manual control, and independent verification of critical measurements.
- (5) **Systemic Vulnerabilities of Digitalisation.**
Beyond deliberate attacks, digitalisation introduces systemic risks through expanded attack surfaces, legacy infrastructures, fragmented patch management, vendor dependencies, limited network segmentation, and human factors. Compromised data integrity poses a particularly critical challenge, as unreliable or manipulated data can undermine predictive analytics and crisis decision-making, underscoring the need for minimum cyber hygiene standards, data governance, and interoperable data frameworks.
- (6) **Institutional Fragmentation and Governance Gaps.**
Many systems remain divided among numerous operators with uneven resources, limiting investment and crisis coordination.

These overlapping pressures highlight the need for integrated management, predictive monitoring, and cross-disciplinary cooperation to maintain water safety and resilience under changing climatic and technological conditions [2–4,16,96–99].

4.3. Types of Risks Affecting Water Distribution Systems (WDSs)

4.3.1. Technical Failures and Natural Disasters

Ageing infrastructure remains a global challenge. Leaks, pipe ruptures, and reservoir failures can lead to secondary contamination, pressure drops, and microbial ingress [3,15,16,39,44,100–104]. In Askøy, Norway (2019), reservoir failure caused *Campylobacter* contamination, affecting 1500 people and resulting in fatalities [105]. In Alamosa, Colorado (2008), poor system maintenance triggered a *Salmonella* spp. outbreak [106]. Natural events exacerbate such vulnerabilities: floods overwhelm treatment plants, earthquakes rupture pipelines, and storms disrupt pumping and storage [6,74].

In the Czech Republic, Prague alone recorded more than 2392 failures in 2008, illustrating the fragility of ageing pipelines [107]. The floods that affected Moravia in 1997 and Bohemia in 2002 demonstrated how natural disasters can compromise both water sources and distribution systems, necessitating large-scale flushing and disinfection [33].

4.3.2. Biological Contamination

Biological agents remain persistent threats, entering through cross-connections, infiltration, or insufficient disinfection. Key pathogens include *E. coli*, *Salmonella* spp., *Giardia*, *Cryptosporidium*, and *Legionella* [108]. Major outbreaks include Milwaukee (1993, *Cryptosporidium*, 400,000 cases), Nokia, Finland (2007, sewage backflow, 8000 cases), and Bergen, Norway (2004, *Giardia*) [109–112]. In the Czech Republic, outbreaks of hepatitis A, dysentery, and salmonellosis have been linked to distribution failures and inadequate disinfection, particularly in smaller systems [107]. Biofilms aggravate these risks by sheltering pathogens, reducing chlorine efficiency, and promoting antibiotic resistance [103,113]. Czech utilities rely mainly on chlorination, which is less effective against protozoa such as *Cryptosporidium* [33,37,49,55,114].

4.3.3. Chemical Contamination

Chemical incidents arise from industrial accidents, agricultural runoff, or treatment failures. Examples include Camelford, England (1988, aluminium sulphate release), and PFAS contamination in Italy [115,116]. Emerging contaminants, pharmaceuticals, and PFASs are of growing concern due to persistence, bioactivity, and resistance to conventional treatment [58,59,90,92,117]. In the Czech Republic, pharmaceuticals have been detected in both surface and groundwater sources [33,56,57], while PFASs are increasingly recognised as critical international pollutants [59,90,115].

4.3.4. Cyberattacks and Sabotage

In this review, the term “cybersecurity threats” is used as a general concept encompassing malicious activities targeting digital systems, cyberattacks refer to specific intentional incidents, and cyber-physical risks describe the resulting impacts on the physical operation of WDSs.

Digitalisation in the water sector brings both significant resilience benefits and new vulnerabilities. Supervisory Control and Data Acquisition (SCADA) systems allow operators to remotely monitor and manage water infrastructure, improving efficiency and response times [118]. However, these systems are also vulnerable to cyber intrusions and manipulation. A well-documented case occurred in Oldsmar, Florida (2021), where hackers attempted to increase sodium hydroxide levels in the drinking-water supply to dangerous concentrations [119–122]. Other reported incidents include an attack on a water utility in Illinois (2011) [123], manipulation of systems in San Francisco (2021) [124], attempted intrusions into Israeli water facilities (2020) [125,126], and a cyberattack in Muleshoe, Texas (2024), which disrupted local operations [127,128]. In Europe, coordinated incidents in

Cologne and Mechernich, Germany (2024), raised concerns about deliberate contamination and underscored potential risks for the North Atlantic Treaty Organization (NATO) infrastructure in the region [129–131].

The Czech Republic has experienced a similar escalation of cyber threats. According to the National Cyber and Information Security Agency (NCIB), 262 cyber incidents were recorded in 2023, nearly double the figure from the previous year [39]. These included ransomware attacks against municipal information systems as well as attempts to infiltrate SCADA-based control of water infrastructure [39,41,132]. While utilities abroad are increasingly deploying advanced IoT sensor networks [20,22,83], which provide continuous data streams and early anomaly detection, most Czech operators continue to rely primarily on traditional SCADA platforms. Although functional, these systems lack the predictive and adaptive capabilities offered by newer solutions, leaving the sector relatively exposed to cyber-physical risks [30,40].

To illustrate the multiple safeguards embedded in the Czech WDS, Figure 2 presents a schematic Risk and Protection Layers map, while Figure 3 summarises current practices in the Czech Republic (source: authors’ own elaboration). The figures demonstrate how successive layers of protection from source water protection and treatment processes to monitoring, control systems, and distribution network management interact to mitigate contamination risks and ensure drinking-water safety. Figure 3 further provides contextual insight into the prevailing operational, monitoring, and infrastructure practices, complementing the conceptual framework shown in Figure 2. The schematic also supports the identification of potential vulnerabilities across the water supply chain, from water resources to consumers.

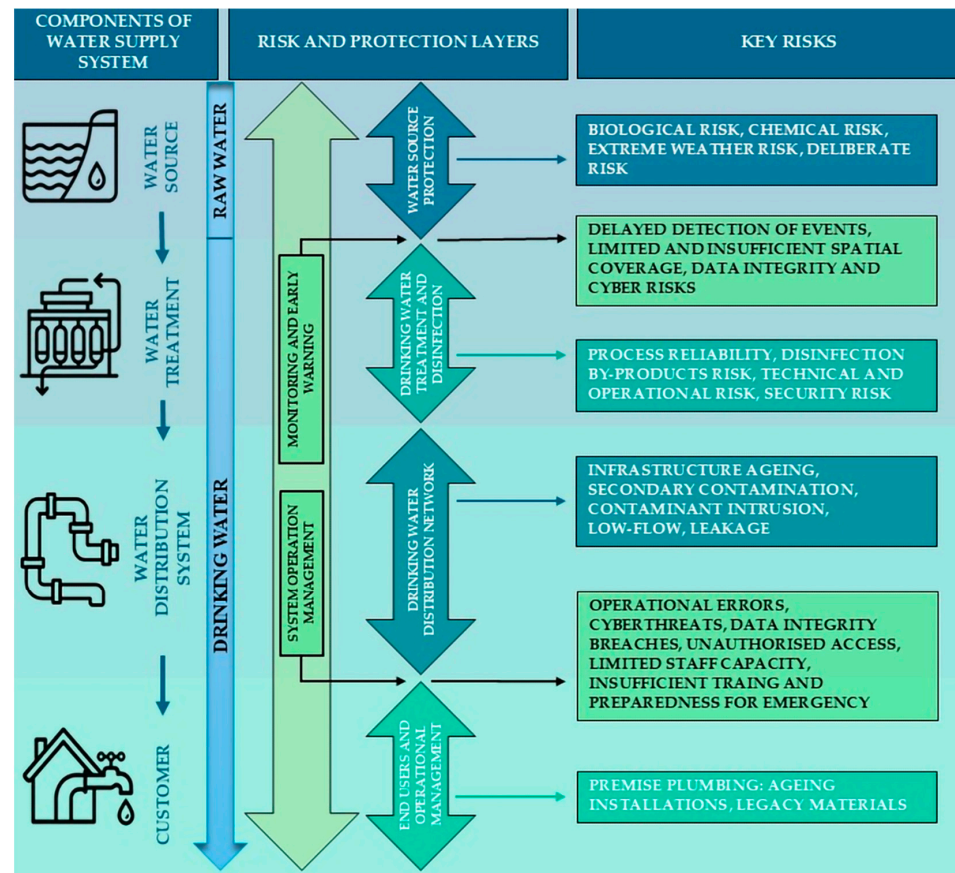


Figure 2. Risk and protection layers map of the drinking-water distribution system in the Czech Republic (source: author’s own elaboration).

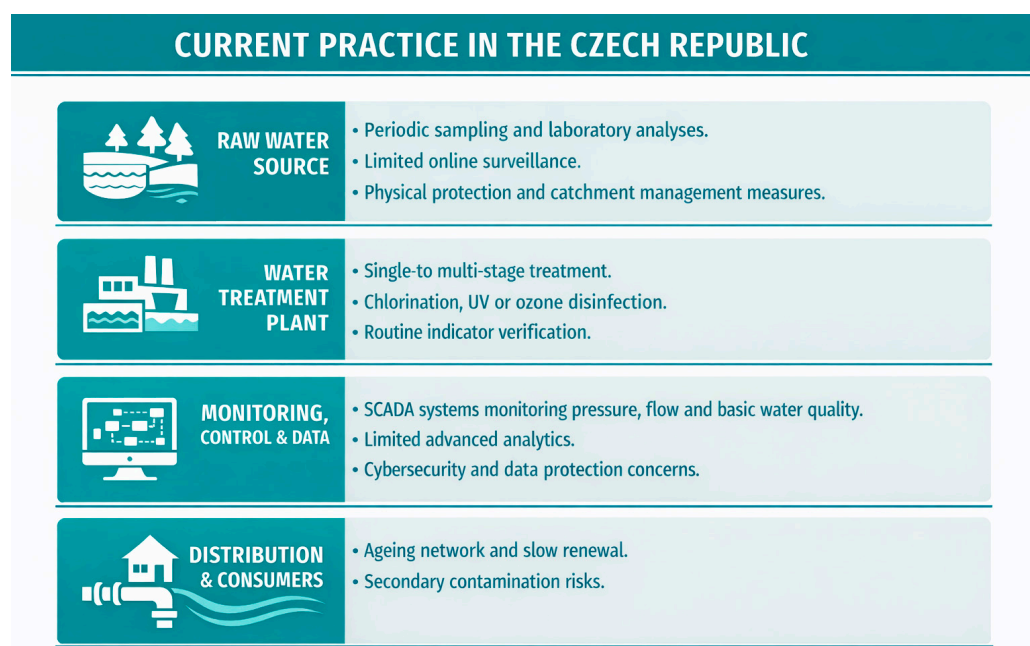


Figure 3. Current practice in the Czech Republic (source: author's own elaboration).

4.4. Overview of Contaminants and Indicators

Drinking-water quality is influenced by three principal categories of contaminants [2,19,133,134]. Physical indicators, such as turbidity, colour, odour, and conductivity, often serve as early warning signals of corrosion, sediment intrusion, or pipe failures. Chemical contaminants include traditional pollutants, such as nitrates, pesticides, and heavy metals, but also an increasing number of micropollutants, such as pharmaceuticals and per- and polyfluoroalkyl substances (PFASs), which are resistant to conventional treatment [28,133–136]. Biological contaminants comprise a wide spectrum of bacteria, viruses, and protozoa, including pathogens such as *E. coli*, *Cryptosporidium*, and *Legionella* [2,108,134].

A critical cross-cutting factor is the presence of biofilms in WDSs. Biofilms provide protective niches for microorganisms, reducing the effectiveness of chlorine residuals and other disinfectants. They also facilitate horizontal gene transfer, promoting the spread of antimicrobial resistance and enabling the persistence of pathogens within supply distribution systems [103,113]. The interplay between biofilms, chemical pollutants, and microbial contaminants highlights the importance of integrated monitoring and advanced treatment strategies [2,19,133–137].

4.5. Contamination Management and Detection Technologies

Effective contamination management combines reliable disinfection, continuous monitoring, and advanced treatment technologies [2,19,137,138]. The goal is to maintain microbiological safety while minimising chemical by-products and ensuring rapid detection of any anomaly [2,139].

4.5.1. Chlorination and Chloramines

Chlorination has been the dominant disinfection method for over a century and remains central to water safety due to its affordability, well-established practice, and strong residual effect in WDSs [140–142]. Free chlorine effectively inactivates most bacteria and viruses but is less efficient in the presence of organic matter, elevated temperature, or ageing pipelines where biofilms accumulate [55,101,143]. To improve residual stability, many utilities use chloramines as secondary disinfectants. Chloramines provide longer persistence

in networks and suppress nitrification, but they can form nitrosamines, compounds of emerging health concern [2].

Booster chlorination, common in the USA and UK, maintains residual disinfectant across large WDSs by adjusting chlorine at multiple points [75,144–146]. This approach is not yet systematically applied in Central Europe, including the Czech Republic, where central chlorination remains predominant [55]. With climate change accelerating chlorine decay, exploring alternative or combined strategies is increasingly necessary [133,134,137].

4.5.2. Monitoring and Biosensors

Traditional monitoring based on periodic sampling and laboratory analysis, though reliable, often delays contamination detection [20,22,23,52,77]. Online sensors and biosensors have therefore become key tools for real-time monitoring of microbial and chemical parameters [147,148]. Electrochemical biosensors enable sensitive detection of heavy metals, pesticides, and pharmaceuticals, while optical and fluorescence-based systems target microbial indicators [147,149].

Microbial biosensors employing genetically engineered organisms can signal toxic compounds [17]. Pilot applications in the Netherlands and during the Flint, Michigan, crisis confirmed the advantages of continuous monitoring [75]. However, Czech utilities still rely mainly on SCADA systems focusing on hydraulic parameters (pressure, flow, residual chlorine), with minimal integration of biosensors or advanced analytics [30]. Broader deployment of portable, low-cost sensors would significantly enhance early-warning capacity, especially in smaller systems [20,25,26,84,87,89].

4.5.3. Emerging and Alternative Technologies

Alternative disinfection and treatment methods are increasingly applied as part of multi-barrier approaches. UV irradiation effectively inactivates protozoa such as *Cryptosporidium* and *Giardia* [150]. Ozone treatment provides strong oxidation, improves taste and colour, and is often combined with granular activated carbon [138]. Both UV and ozone lack residual effects, limiting their standalone use in water distribution systems.

Nanomaterials, including TiO₂ photocatalysts, silver nanoparticles, and carbon-based composites, show promising antimicrobial and pollutant-removal capacities [21], though issues of cost, stability, and nanoparticle toxicity remain [136].

Integrated combinations, such as UV + chlorine or ozone + activated carbon, are therefore recommended by the WHO (2022) [2] to achieve high removal efficiency and maintain residual safety throughout the system.

4.6. Lessons from International and Czech Case Studies

Global case studies demonstrate that even advanced systems remain vulnerable. Natural disasters amplify risks where infrastructure is ageing, and deliberate physical or cyber-attacks are increasing, highlighting the geopolitical dimension of water security [5,6,13,14].

The Czech experience reflects these global lessons. While compliance with EU standards remains high, failures in Prague (2008) [151], contamination associated with the 1997 and 2002 flood events [152], and pharmaceutical detections [56,57] reveal persistent vulnerabilities. Compared to Western Europe, Czech systems face lower micropollutant loads but greater challenges from fragmented ownership, limited digitalisation, and insufficient renewal rates [8,13,15,16,19,31,33,35,37,39,40,45,49,69,71,76]. Addressing these weaknesses will require integrated protection strategies combining infrastructure renewal, continuous monitoring, multi-barrier disinfection, IoT-enabled detection, and robust institutional preparedness. Only a systemic approach can meet both traditional and emerging risks in the context of climate change and cyber-physical convergence [3,5,6,9,19,20,28,30,38,39,42,47,56,70,76].

5. Discussion

The Czech Republic represents a specific case within the broader European and global context of drinking-water safety. Compared to many countries, it consistently demonstrates high water quality and strong legislative control, but it lags in digitalisation, predictive monitoring, and resilience to emerging risks such as pharmaceuticals, biofilms, and cyberattacks.

5.1. Comparison with International Experience

Long-term monitoring in the Czech Republic confirms that exceedances of hygienic limits are rare, with compliance often surpassing EU requirements [31,33]. This contrasts with parts of Southern and Eastern Europe, where contamination with nitrates, pesticides, or microbiological parameters remains a significant issue [15,153]. Overall, available monitoring data indicate that drinking-water quality in the Czech Republic is consistently high in a European context.

International comparison, however, reveals several divergences [1,2,7,8,15,35,40,45,107]. Pharmaceuticals and other micropollutants are increasingly integrated into monitoring frameworks in Western Europe and the USA, whereas they remain outside binding Czech standards despite repeated detections in raw water [2,19,56,57]. Similarly, international research places strong emphasis on biofilms as drivers of microbial regrowth and antibiotic resistance [39,103,113], while this topic has received relatively limited attention in national practice and implementation. Digitalisation represents another major gap.

Most Czech utilities rely on SCADA systems with limited predictive capacity [17,19,20,23,25,30,40,41,83], while countries such as the USA, Israel, and Scandinavia already deploy IoT-based sensor networks and machine learning models for anomaly detection and predictive water management [124–126]. This technological lag limits the ability to detect failures or contamination at an early stage. Cyber incidents in the Czech Republic nearly doubled between 2022 and 2023, reaching a number of 262 [39]. Although less severe than high-profile cases abroad (e.g., Oldsmar, Florida, 2021; Israel, 2020), the trend indicates growing vulnerability [121,122,125,126].

The infrastructure age is a shared challenge across Europe. Much of the Czech WDS was constructed before 1980, yet renewal rates remain insufficient [42]. In contrast, more centralised utilities in Western Europe and North America often achieve higher renewal rates due to unified investment frameworks [14].

The Czech Republic thus represents a case illustrating how a drinking-water supply with historically high water quality and strong legislative control may nevertheless face growing vulnerability due to delayed digitalisation, ageing infrastructure, and insufficient preparedness for emerging risks.

Biofilms within water distribution systems do not function solely as passive reservoirs of microorganisms but also constitute active microenvironments that can influence the behaviour of chemical micropollutants through processes, such as sorption, gradual release, and local microbial transformation, while simultaneously reducing the effectiveness of residual disinfection. This creates a risk that both contaminant concentrations and microbial loads may vary spatially and temporally, rather than being determined solely by water quality at the treatment plant outlet.

From an operational perspective, these dynamics imply the need for: (I) targeted monitoring at hydraulically and operationally “critical” network sections characterised by long residence times, low flow conditions, or elevated biofilm occurrence; (II) the application of combined barrier strategies, including optimisation of residual disinfection, periodic flushing, and, where appropriate, advanced treatment technologies at the treatment plant aimed at reducing precursor substances; and (III) the integration of hydraulic information

such as residence time and mixing patterns with monitoring data to support more accurate interpretation of anomalies and improved operational decision-making.

5.2. Comparative Synthesis

The Czech Republic, therefore, shows a dual profile [31,32,35,37,38,40,42,44,45]:

- Strengths—high drinking-water quality, robust EU-aligned legislation, dense infrastructure network, and long tradition of chlorination ensuring residual disinfection.
- Weaknesses—ageing pipelines, highly fragmented ownership, limited adoption of digital tools, and insufficient integration of emerging contaminants into standards.

By comparison, the international experience shows [2,3,7,19,90,97,117,133,142]:

- Southern/Eastern Europe—more frequent exceedances of nitrates and pesticides, but less fragmented institutional frameworks.
- Western/Northern Europe and USA/Israel—greater emphasis on biofilms, pharmaceuticals, PFASs, and advanced digitalisation (IoT and AI-based predictive systems), together with faster infrastructure renewal.

The coexistence of consistently high drinking-water quality and increasing system vulnerability can be attributed to several underlying structural drivers. Historically developed infrastructure and regulatory frameworks have established a stable foundation for hygienic safety; however, post-1990 investment cycles and persistently insufficient renewal rates have resulted in the gradual accumulation of technical debt within distribution networks. Tariff policies and a heterogeneous ownership structure constrain the ability to mobilise capital for large-scale infrastructure renewal and simultaneously hinder the harmonisation of methodologies related to asset management and monitoring standards.

Regulatory incentives remain strong with respect to compliance with hygienic limit values, yet are comparatively weaker in areas such as digitalisation, data interoperability, and preparedness for cyber-physical scenarios. Finally, institutional capacities vary substantially between large and small water utilities, a disparity that translates into uneven levels of prevention, early detection, and crisis management across the sector.

5.3. Future Perspectives

Public trust and risk communication are increasingly recognised as essential pillars of drinking-water supply resilience [69]. While technical measures, such as disinfection, monitoring, and predictive modelling, ensure operational safety, public perception often determines the effectiveness of crisis response [1,3,5,7,16,27,62,71,77]. From a modelling perspective, the water network can be represented as a graph composed of nodes and links, enabling the analysis of hydraulic behaviour and the optimisation of sensor placement. International experience shows that inadequate communication during contamination incidents can undermine trust and prolong public health impacts [15,153]. In the Czech Republic, communication is typically coordinated by regional health authorities and utilities, but systematic public engagement remains limited. Potential improvements may include transparent communication protocols, digital alert systems, and regular public information campaigns [44,45,49,57,61,69,71,72,76].

Building on its strong foundations, the Czech Republic must now address structural and technological weaknesses to meet modern challenges [2,14,16,19,28,37–44,47,49,55–57,69,72,92,154].

The implementation of key measures such as network renewal, online monitoring, digital decision-support tools, and advanced water treatment technologies represents a typical trade-off between capital expenditures (CAPEXs), associated with infrastructure renewal and technology deployment, and operational expenditures (OPEXs), including operation, maintenance, energy consumption, and staffing requirements. While underinvestment may

appear cost-saving in the short term, it systematically increases long-term expected losses arising from asset failures, supply interruptions, and the public health consequences of contamination events.

From a policy perspective, it is therefore essential to explicitly link hygienic safety objectives with asset management and financing strategies. This requires a coordinated approach that combines tariff-based instruments, targeted public funding schemes, and, where feasible, shared regional investment mechanisms. Such arrangements can reduce financial barriers, particularly for smaller water utilities, while supporting more resilient and cost-effective long-term system management. The interacting technical, financial, digital, and institutional dimensions of this systemic transition are synthesised in Figure 4, which illustrates the proposed pathways toward long-term resilience in the Czech water sector.

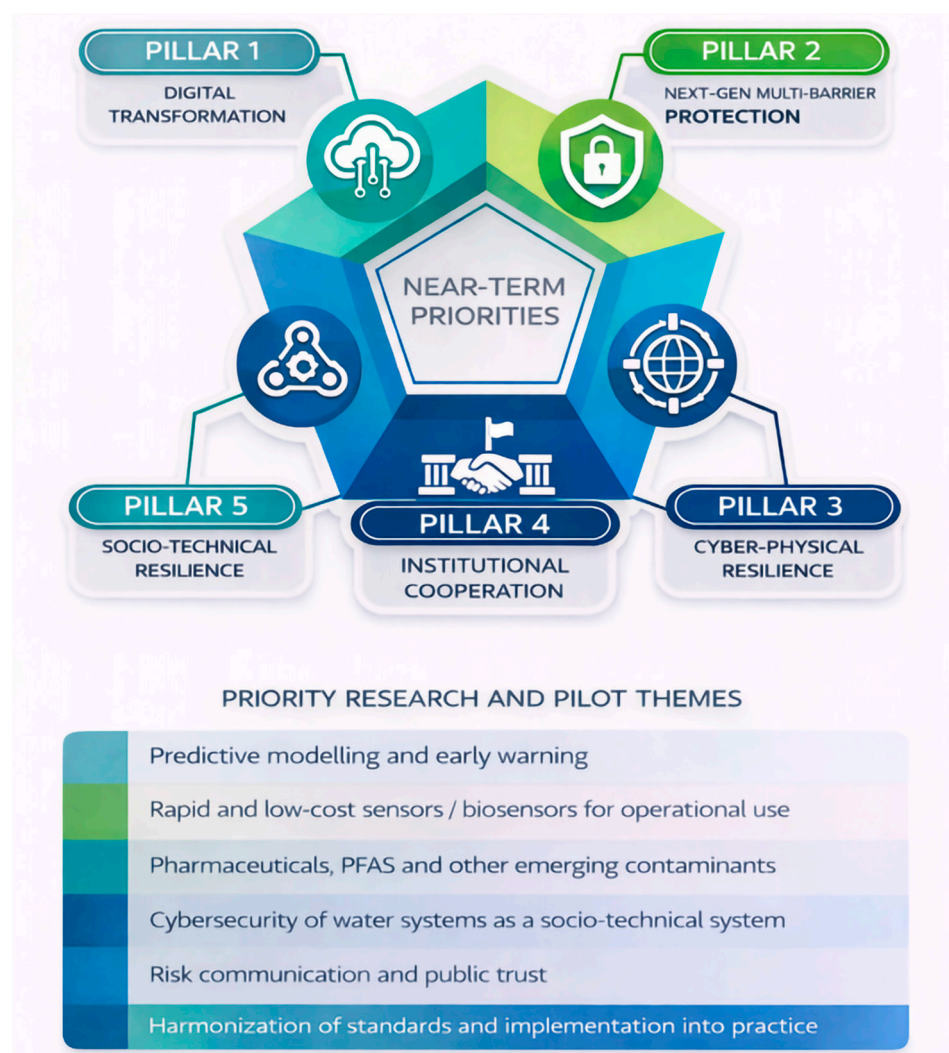


Figure 4. Future pathways for resilient water supply (source: author’s own elaboration).

Key steps include:

- Accelerated renewal of ageing infrastructure, supported by unified methodologies for condition assessment.
- Strengthening digitalisation and cybersecurity, learning from countries already deploying IoT and AI for predictive water management.
- Integration of emerging contaminants, both pharmaceuticals and biofilm-related pathogens, into monitoring and regulation, in line with EU and WHO recommendations.

- Institutional consolidation and inter-municipal cooperation to reduce fragmentation and enable long-term investment.

These measures would align the Czech water sector with international best practices, improve resilience against evolving threats, and ensure that the country's historically strong record of water safety remains sustainable under future climatic, technological, and geopolitical pressures.

5.4. Socio-Technical Aspects, Risk Communication, and Public Trust

The resilience of drinking-water supply systems is determined not only by the technical condition of infrastructure and the level of water treatment but also by institutional arrangements, human factors, and the way risks are communicated [2,16,18,19]. This perspective corresponds to socio-technical research approaches that regard risk communication and public trust as integral components of drinking-water safety management. These socio-technical aspects significantly influence the ability of WDSs to respond to contamination events, crisis situations, and emergencies while simultaneously maintaining public trust, especially in cases where the technical management of an incident is successfully communicated [16,68,69,75].

International approaches to drinking-water safety management, particularly the concept of Water Safety Plans, consider risk communication and public engagement to be essential elements of comprehensive water system governance [2,16,19]. Experiences from the United States, Canada, Australia, Scandinavia, and the Netherlands demonstrate that systematic, transparent, and timely communication with the public enhances overall system resilience and contributes to the long-term maintenance of consumer trust, even during the implementation of new technologies or the management of crisis events [5,8–10,24,25,28,29,106,110,111,115,116,119,120,124,126,129].

In the conditions of the Czech Republic, technical measures related to drinking-water quality and crisis management are generally well developed; however, socio-technical aspects are still addressed rather implicitly and without a unified framework. The fragmented structure of water utility operators, limited standardisation of crisis communication, and the predominance of traditional operational approaches complicate consistent public information and the systematic use of lessons learned from crisis exercises [61–68,72]. In the event of more serious contamination incidents, these factors may weaken response coordination and negatively affect public risk perception.

With the ongoing digitalisation of drinking-water supply systems, the socio-technical dimension is gaining further importance [13,16,19,23]. The transition toward IoT-based monitoring and data-driven management requires not only technical investments but also changes in organisational culture, systematic staff training, and the integration of cybersecurity risks into Water Safety Plans [16,20,86]. Human factors, institutional preparedness, and the quality of internal and external communication therefore represent key determinants of overall system resilience in an environment of increasing technological and cyber-physical threats [13,41,75,79].

From the perspective of future development of the water sector, it is essential to systematically integrate technical risk assessments with institutional and communication aspects that shape risk perception and public trust. These socio-technical aspects provide an important framework for strengthening the resilience of drinking-water supply systems and extend purely technical measures by incorporating institutional and societal dimensions of drinking-water safety [16,26,38,142].

6. Research Gaps

To ensure that the identified research gaps are actionable and relevant for practice, this review distinguishes between three complementary priority levels: (1) immediate, safety-critical needs that directly enhance the capacity for early detection and effective management of incidents; (2) medium-term implementation-oriented directions focused on piloting and operational integration of emerging technologies and standards; and (3) long-term strategic research directions aimed at advancing fundamental process understanding and enabling systemic institutional and governance reforms. The following subsections are therefore structured according to this framework and, for selected research areas, also outline indicative logics for pilot and demonstration projects.

Although the Czech Republic, similarly to many other developed countries, has achieved a consistently high standard of drinking-water quality, several research gaps remain critical for ensuring the long-term resilience of water distribution systems. These gaps closely align with the research priorities highlighted in the abstract, including predictive modelling and early warning, IoT-based sensing, pharmaceuticals and PFASs, biofilm dynamics, rapid detection methods, and socio-technical dimensions of water system management. Addressing these interconnected gaps is essential for translating high regulatory compliance into sustained operational resilience under evolving environmental, technological, and security pressures [20,25,26,59,81,84,87,90,100,117].

6.1. Predictive Modelling and Early Warning

Monitoring in the Czech Republic remains primarily based on periodic sampling and laboratory analyses, which limits the ability to respond to sudden contamination events [3,7,38,40,56,57,69,72,76]. Predictive modelling based on machine learning and artificial intelligence has the potential to substantially enhance crisis preparedness by enabling the early forecasting of failures or contamination events in WDSs. In this context, digital twins increasingly combine data-driven models with hydraulic simulations implemented in tools such as EPANET, where the underlying water network topology governs flow paths, residence times, and contaminant transport. However, the real-time integration of EPANET-based hydraulic models with continuous monitoring data and advanced analytics remains uncommon in practice and represents a key research priority [13,20,40,85,100].

Priority directions for the application of artificial intelligence and machine learning in water distribution systems include several complementary areas. These comprise: (I) real-time anomaly detection based on hydraulic and water quality signals (e.g., pressure, flow, residual chlorine, turbidity) to enable early identification of failures or contamination events; (II) predictive modelling of pipe failures and optimisation of renewal strategies within risk-based asset management frameworks; (III) hybrid modelling approaches that integrate hydraulic simulations (e.g., EPANET-based digital twins) with data-driven inference to improve estimates of contaminant propagation and to inform optimal sensor placement; and (IV) detection of cyber incidents at the operational technology level through analysis of anomalies in control commands and telemetry data. In the Czech context, a critical enabling condition for the practical deployment of these approaches is the definition of a “minimum data standard”, ensuring that AI/ML methods remain applicable not only to the largest utilities but also across smaller and medium-sized operators.

6.2. IoT Sensors and Digitalisation

The digitalisation of the Czech WDS trails international practice. While advanced IoT-based platforms for continuous monitoring are increasingly adopted in the USA, Israel, and Scandinavian countries, Czech utilities predominantly operate SCADA systems with limited functionality (Table 5) [123,124]. Research is needed to evaluate and deploy low-cost,

robust IoT sensors for real-time monitoring of residual chlorine, turbidity, and microbiological indicators. Another critical research direction concerns the cybersecurity of IoT-based systems, as digitalisation inevitably increases vulnerability to cyberattacks [20,39,83].

Table 5. Comparison of traditional SCADA systems and advanced IoT-based solutions in water utilities (source: author’s own elaboration).

| Aspect | Traditional SCADA System | Advanced IoT-Based Solutions |
|-------------------------|---|---|
| Data acquisition | Periodic measurement of a limited number of parameters (flow, pressure, residual chlorine). | Continuous multi-parameter and real-time monitoring (turbidity, microbiology, residual disinfectants, PFASs, etc.). |
| Communication | Centralised architecture often relies on proprietary protocols. | Decentralised, cloud-integrated communication based on open-standard protocols (MQTT, OPC UA, LoRaWAN). |
| Predictive capability | Reactive—alarms are generated only after an incident occurs. | Predictive—AI/ML models forecast operational failures, anomalies, and potential contamination events. |
| Coverage | Typically limited to main facilities (treatment plants, pumping stations). | Sensor networks are deployed throughout the entire distribution system, including remote sites and households. |
| Cybersecurity | Moderate level—vulnerable to targeted SCADA intrusions. | Broader attack surface, but improved intrusion detection, encryption, and anomaly response are possible. |
| Cost and scalability | High initial CAPEX with limited flexibility. | Modular, scalable architecture with lower per-sensor cost and simplified expansion. |
| Flexibility/integration | Rigid and difficult to expand, with limited interoperability. | Highly adaptable and interoperable, fully integrable with digital twin and smart city ecosystems. |

Proposed are the following pilot demonstration activities (medium-term priority):

- (1) Online early-warning pilot in a medium-sized urban network.
A pilot implementation of an online early-warning system could be conducted in a representative medium-sized water distribution network over a period of 6–12 months. The pilot would combine sensors measuring residual chlorine, turbidity, pressure, and conductivity with basic anomaly detection algorithms. Evaluation metrics should include detection time, false alarm rates, operational costs, and the system’s ability to localise abnormal events within the network.
- (2) Hybrid digital twin pilot (hydraulic + data-driven).
A second pilot could focus on the development of a hybrid digital twin integrating EPANET-based hydraulic modelling with data-driven inference over a period of 12–18 months. The primary objectives would be improved estimation of water residence times, identification of critical network nodes, and simulation of contamination scenarios. Performance should be assessed based on predictive accuracy and practical usability in emergency and crisis management contexts.
- (3) OT cyber hygiene baseline pilot for small utilities.
A third pilot demonstration could target the establishment of an OT cyber hygiene baseline at a small water utility over approximately six months. Key components would include network segmentation, patch and update management, access control audits, and the implementation of a basic incident response checklist. Success metrics should include the number of identified vulnerabilities, response times to simulated incidents, and the outcomes of staff training activities.

6.3. Pharmaceuticals and Emerging Contaminants

Pharmaceuticals have been repeatedly detected in Czech water sources, yet binding thresholds are absent, and removal technologies are not systematically implemented [33,37,45,49,57]. PFASs are a globally growing concern, but Czech monitoring remains limited and unregulated, contrasting with the strict limits recently introduced by the EPA in the USA [19]. Research should focus on systematic monitoring, risk assessment of chronic exposure, and testing advanced removal technologies (activated carbon, oxidation, membranes) under local conditions [56,115,133,138].

6.4. Biofilms and Microbial Risks

Biofilms act as reservoirs for pathogens, opportunistic bacteria, and antibiotic resistance [103,113]. In the Czech Republic, systematic research on biofilms in the water supply system is lacking. Priorities include studying biofilm growth in different pipe materials, their role in microbial regrowth, and evaluating disinfection strategies [9,139,140,142].

6.5. Cybersecurity of Water Infrastructure

With 262 cyber incidents recorded in 2023, almost double compared to the previous year [39], cybersecurity has become one of the fastest-growing threats to Czech water infrastructure [39–41]. Unlike in the USA or Israel, where severe intrusions have already been documented [119,120,127,128], most Czech cases have so far been less damaging [155,156]. However, the growing number of attacks highlights the need for research into intrusion detection systems, system redundancy, and risk modelling. Organisational preparedness, staff training, and the human factor also represent underexplored areas that could critically influence resilience [28,78].

6.6. Socio-Technical Integration in the Czech Water Sector

Although the resilience of drinking-water supply systems is increasingly assessed not only from a technical perspective but also in terms of human factors, institutional arrangements, and governance structures, the socio-technical approach remains only partially implemented in current Czech practice. This is particularly relevant in the Czech Republic, where the sector is highly fragmented, with numerous asset owners and operators, and where organisational capacities differ substantially, especially in relation to digitalisation, data management, and preparedness for emergency situations.

There is therefore a clear need to strengthen the integration of technical disciplines with public health protection, emergency management, public administration, and social sciences. Within the Czech context, the following medium- to long-term directions can be recommended:

- (1) **Joint Mapping of Roles and Decision-Making Processes.**
Technical risk assessments within distribution networks (e.g., vulnerable nodes, failure impacts, contamination risks) should be systematically linked with a clear delineation of responsibilities, information flows, and potential decision-making bottlenecks. The resulting outputs should inform the revision and updating of Water Safety Plans.
- (2) **Risk Communication and Public Trust.**
Research should evaluate the clarity and effectiveness of warning messages and public recommendations, as well as examine public perceptions of continuous monitoring, digitalisation measures, and interventions addressing micropollutants (e.g., pharmaceuticals and PFASs).
- (3) **Assessment of Operator Capacities.**
A comparative evaluation of large and small operators should be conducted with regard to emergency procedures, cybersecurity preparedness, data management

capabilities, and the ability to share information under harmonised standards. The objective is to identify capacity gaps and to define minimum baseline requirements applicable across the sector.

(4) **Integrated Exercises (Technical and Communication Dimensions).**

Tabletop or simulation-based exercises should be implemented to combine technical scenarios (e.g., contamination events, cyber incidents, pressure anomalies) with an evaluation of decision-making processes, information exchange, and public communication strategies.

The incorporation of socio-technical approaches into the Czech research and regulatory environment may facilitate the practical implementation of recommendations, reduce disparities between large and small operators, and enhance the long-term safety and reliability of drinking-water supply systems.

6.7. *Infrastructure Renewal and Asset Management*

Ageing of WDSs is a fundamental challenge [2,7,101]. A unified methodology for assessing technical condition is missing, meaning many failures are detected only after incidents occur [44]. Research is required to develop predictive asset management tools, optimise investment planning, and prioritise renewal of critical infrastructure.

6.8. *Legislative Framework and Risk Communication*

Although Czech legislation is harmonised with EU directives, it does not yet include pharmaceuticals, PFASs, or biofilm-related risks [2,45,49,51–54]. Research should support the integration of emerging contaminants into binding standards. Furthermore, strategies for public risk communication are underdeveloped, and systematic studies should explore how to strengthen consumer trust during contamination events [11,16,69,110].

6.9. *Harmonisation of International Standards*

Although hygiene requirements in the Czech Republic are harmonised with EU directives [2,45,51–54,95], significant differences remain compared to WHO guidelines and EPA regulations. As shown in Table 4, values for parameters such as nitrites, radon, PFASs, and selected heavy metals vary considerably across jurisdictions [2,19,51–54]. These discrepancies complicate international comparison and hinder coordinated responses to emerging contaminants.

The EU framework generally applies the precautionary principle, setting conservative thresholds for parameters such as pesticides and nitrates [54,95]. WHO guidelines, by contrast, reflect pragmatic feasibility in low-resource settings, which leads to less strict limits for certain indicators, such as nitrites (3 mg/L vs. 0.5 mg/L in the EU). At the other extreme, the EPA adopts stringent values for emerging contaminants, particularly PFASs, where thresholds as low as 0.004 µg/L for PFOA and PFOS have been introduced in response to domestic crises such as the one in Flint and widespread PFAS contamination [2,19,58,59].

For the Czech Republic, which is fully aligned with EU legislation, this divergence creates challenges for both risk communication and international collaboration. Consumers may struggle to understand why limits differ so widely across countries, while operators and regulators must balance the precautionary EU approach with the need for global consistency [2,51–54,95].

Future research should therefore examine:

- the toxicological basis of current standards and their protective capacity;
- the socio-economic feasibility of implementing stricter or more lenient thresholds;
- pathways for policy harmonisation, including evidence-based dialogue across the WHO, EU, and EPA frameworks.

Such work would not only strengthen the scientific justification for regulatory values but also support the alignment of Czech and EU practice with global standards, ensuring that protection remains both effective and practicable in diverse socio-economic contexts [2,51–54,95]. The following Table 6 summarises the main thematic areas where further research is required. Key gaps relate to infrastructure renewal, digitalisation, emerging contaminants, such as pharmaceuticals and PFASs, biofilm-associated microbial risks, crisis preparedness, and the harmonisation of international drinking-water standards [80,85,90,117,134,140].

Table 6. Current situation and research needs in drinking-water safety and infrastructure resilience (source: author’s own elaboration).

| Thematic Area | Current Situation | Research Needs |
|--|---|---|
| Predictive modelling and early warning | Monitoring is based mainly on periodic sampling and SCADA systems with limited forecasting capability. | Integration of hydraulic models with real-time data; application of AI/ML for prediction of failures and contamination events. |
| IoT sensors and digitalisation | SCADA dominates, IoT deployment remains limited; cybersecurity incidents are increasing. | Development and testing of low-cost IoT sensors; real-time monitoring of chlorine, turbidity, and microbiology; cybersecurity frameworks for digital systems. |
| Pharmaceuticals and PFASs | Detected in raw water; no binding limits; limited treatment technologies applied. | Systematic screening and risk assessment; pilot testing of activated carbon, oxidation, and membrane technologies; alignment with EU and EPA standards. |
| Biofilms and microbial risks | Biofilm risks are insufficiently studied; reliance on chlorination may be inadequate. | Research on biofilm dynamics across pipe materials; evaluation of disinfection efficiency; assessment of antibiotic resistance mechanisms. |
| Cybersecurity of infrastructure | 262 incidents were reported in 2023; SCADA systems remain vulnerable; preparedness levels vary. | Development of intrusion detection and redundancy systems; modelling of cyber-physical risks; human factors in infrastructure resilience. |
| Infrastructure renewal and asset management | Ageing networks and insufficient renewal rates; lack of unified methodology. | Predictive asset management tools; condition-based renewal planning; optimisation of investment prioritisation. |
| Legislative framework and risk communication | EU-harmonised hygiene law; lack of standards for pharmaceuticals, PFASs, and biofilms; limited public engagement. | Integration of emerging contaminants into legislation; transparent communication protocols and digital alert systems. |
| International standards harmonisation | Large differences among EU, WHO, and EPA limits (e.g., nitrites, PFASs, radon). | Comparative toxicological studies; socio-economic feasibility of stricter thresholds; evidence-based policy dialogue for international alignment. |

The identified research gaps are therefore understood not only as academic questions but also as practical inputs for pilot demonstrations and the development of minimum operational standards. Priority is given to directions that support early-detection capabilities, standardisation of operational data, and the reduction in uneven preparedness levels across water utilities.

7. Limitations

This review has several limitations that should be acknowledged. First, although the literature search was broad, the synthesis was intentionally narrowed to 156 key studies in order to maintain analytical focus, clarity, and a reasonable article length. As a result, some relevant international studies may not have been included. Second, differences in research design, monitoring practices, national regulatory frameworks, and methodological approaches across countries limit the direct comparability of certain findings. Third, a number of technical reports, incident summaries, and the grey literature sources available in the Czech Republic are not indexed in international scientific databases, which may reduce the visibility and integration of locally generated knowledge into global research contexts.

The literature search was finalised on 26 December 2025, which defines the temporal scope of the evidence considered. Given the rapid evolution of key domains addressed in this review, particularly cybersecurity and the regulation of emerging contaminants, specific limit values, recommended practices, and threat landscapes may change after this cut-off date. The conclusions should therefore be interpreted as a synthesis reflecting the state of knowledge up to this reference point.

Furthermore, this article is designed as a qualitative, contextual review and does not include formal quantitative risk assessment, meta-analysis, or detailed economic modelling. While this approach enables an integrated interpretation of diverse risk dimensions and governance contexts, quantitative risk assessment and techno-economic analyses are recognised as essential directions for future research, particularly for investment prioritisation and estimation of incident impacts.

The selection of international case studies also represents a potential limitation. Case studies were chosen based on: (I) their relevance to water distribution systems, including contamination events, infrastructure failures, or cyber incidents; (II) the availability of sufficiently documented data and clearly articulated lessons learned; (III) their transferability to EU and Czech conditions in terms of institutional frameworks and applied technologies; and (IV) an effort to ensure thematic and geographical diversity. Nevertheless, alternative selection criteria could yield different illustrative examples.

Finally, as with any thematic synthesis, there is a risk of confirmation bias, whereby studies supporting anticipated conclusions may be preferentially emphasised. To mitigate this risk, the review explicitly sought contrasting findings, including studies reporting divergent conclusions regarding the effectiveness of monitoring approaches or risk management strategies. Interpretations were compared across regions, and key claims were cross-validated using multiple source types, including peer-reviewed studies, authoritative guidelines, and documented case reports.

8. Conclusions and Recommendations

At the same time, however, the findings confirm that even under conditions of high regulatory compliance, structural weaknesses typical of developed countries persist. These include ageing infrastructure, fragmented ownership and operational governance arrangements, and the comparatively slower adoption of advanced digital tools. Emerging and compound risks are also becoming increasingly prominent, particularly micropollutants (including pharmaceuticals and PFASs), biofilm-related processes within distribution systems, and the growing relevance of cyber threats, which may directly affect the physical operation of water supply facilities. Hydrological extremes (droughts and floods) constitute an additional amplifying factor, exerting increasing pressure on both water resources and the operational stability of distribution networks.

Ensuring long-term resilience, therefore, requires a systemic approach that integrates infrastructure renewal and asset management with modern operational control, strengthens

preparedness across diverse threat categories, and enhances coordination among key stakeholders within the sector. A shift from predominantly reactive problem-solving towards preventive risk management is essential, grounded in data-driven decision-making, the identification of critical network nodes, and harmonised operational and security procedures. In current Czech practice, monitoring remains largely based on periodic sampling and laboratory analyses, which limits the capacity to detect rapid changes in real time. Expanding continuous monitoring at critical points within the distribution system should therefore represent a strategic priority.

8.1. Recommendations for Practice

Based on the above findings, the following recommendations are proposed to strengthen both operational resilience and long-term system sustainability in the Czech water sector.

- (1) Accelerate the renewal of critical network components through risk-based asset management, taking into account pipe age, failure frequency, operational significance, and potential impacts on consumers, supported by the systematic collection and evaluation of operational data.
- (2) Establish a minimum standard for continuous monitoring at operationally critical points (e.g., residual disinfectant concentration, turbidity/conductivity, pressure, and flow) and harmonise evaluation and reporting procedures across utilities.
- (3) Strengthen the cybersecurity of control systems, including network segmentation, access control management, secure data backup, incident response procedures, and staff training. Digital tools, including artificial intelligence (AI), should be implemented gradually and securely, with clearly defined responsibilities, human oversight, and robust data governance rules. In this context, AI is particularly relevant for early warning systems, failure prediction, anomaly detection in operational datasets, and the timely identification of deviations in disinfectant dosing. However, the use of AI is appropriate only where sufficient data quality and sound governance structures are ensured. Key considerations include model reliability and interpretability (explainability), the risk of erroneous decisions under changing operational conditions, cybersecurity vulnerabilities, the protection of sensitive operational data, and the preservation of human decision-making authority in critical interventions.
- (4) Integrate emerging contaminants into decision-making and monitoring frameworks, including the development of clear response procedures for the detection of micropollutants and the strategic planning of treatment technologies where required by the risk profile of water sources.
- (5) Improve biofilm management through a combination of operational measures, targeted diagnostics, and verification of disinfection effectiveness across different pipe materials and operational regimes.
- (6) Enhance crisis preparedness and communication by expanding exercise scenarios to include cyber incidents and intentional contamination events, harmonising communication protocols, and strengthening public trust through transparent and consistent procedures.

8.2. Recommendations for Research

- (1) Predictive management and early warning systems: Integration of sensors, hydraulic models, and artificial intelligence, including advanced machine learning techniques, to enable anomaly detection, early warning, and decision support. This should include validation of applicability across different operational contexts (e.g., varying utility sizes, source types, network configurations, and operational regimes).

- (2) Micropollutants (pharmaceuticals, PFASs): Systematic mapping of occurrence under Czech conditions, assessment of long-term low-level exposure risks, and evaluation of the effectiveness of advanced removal technologies.
- (3) Biofilms: Investigation of regrowth mechanisms and resistance patterns, as well as assessment of the effectiveness of control strategies depending on pipe material and operational conditions.
- (4) Cyber-operational resilience: Intrusion detection, system redundancy, operational robustness, and the role of the human factor in maintaining secure and reliable system performance.
- (5) Risk communication: Consumer responses during incident situations, the use of digital alert channels, and strategies for restoring public trust following service disruptions or contamination events.

8.3. Recommended Phased Implementation Framework

- (1) Period of 0–12 months: Establishment of a minimum security and monitoring baseline, including continuous measurement at operationally critical points and the implementation of basic cybersecurity measures for control systems.
- (2) Period of 1–3 years: Development of risk-based asset management practices, targeted renewal of the most vulnerable network components, and expansion of data records and performance indicators (KPIs).
- (3) Period of 3+ years: System-wide strengthening of resilience, including the establishment of harmonised data and data-sharing standards, improved interoperability, pilot projects for advanced operational management, regular training and simulation exercises, and the development of shared regional capacities to support smaller utilities.

8.4. Final Synthesis

The Czech water sector stands out as one of the safest in Europe, largely due to its very high compliance with drinking-water quality standards and strong legislative oversight supporting monitoring and disinfection practices. These foundations provide a solid basis for long-term water security. Nevertheless, the sustainability of this achievement is increasingly challenged by ageing infrastructure, institutional fragmentation, delayed adoption of digital tools, and insufficient preparedness for emerging risks, such as pharmaceuticals, biofilms, and cyber threats. Although cyber incidents in drinking-water distribution systems (WDSs) have so far remained relatively limited in the Czech context, the ongoing digitalisation of water utilities indicates that cyber-physical risks represent an emerging and increasingly critical dimension of future drinking-water security.

Ensuring future resilience will therefore require a systemic approach that combines accelerated investment in infrastructure renewal with the widespread deployment of predictive digital technologies, the integration of emerging contaminants into regulatory frameworks, and enhanced cyber-physical preparedness. If these challenges are effectively addressed, the Czech Republic will not only safeguard its strong record of water safety but may also serve as a reference model for other Central European countries facing similar infrastructural, technological, and institutional pressures. More broadly, this case illustrates that sustained regulatory compliance must be accompanied by institutional coordination, digital adaptation, and proactive risk governance in order to ensure long-term resilience.

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